

GOLDEN-CHEEKED WARBLER (*DENDROICA CHRYSOPARIA*)  
HABITAT FRAGMENTATION IN TRAVIS COUNTY, TEXAS: A  
REMOTE SENSING AND GEOGRAPHICAL INFORMATION SYSTEM  
ANALYSIS OF HABITAT EXTENT, PATTERN AND CONDITION

A Thesis

by

MICHAEL EDWIN MOSES

Submitted to the Office of Graduate Studies of  
Texas A&M University  
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Major Subject: Rangeland Ecology and Management

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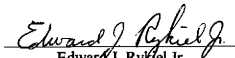
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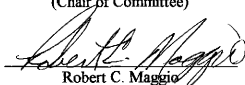
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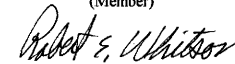
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## ABSTRACT

Golden-Cheeked Warbler (*Dendroica chrysoparia*) Habitat  
Fragmentation in Travis County, Texas: A Remote Sensing and  
Geographical Information System Analysis of Habitat Extent, Pattern  
and Condition. (December 1996)

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Wild species in human populated areas face continuous habitat loss and fragmentation. This study focused on past and present declines of the Golden-cheeked Warbler (GCW), a neotropical migrant dependent on a highly specialized set of habitat factors. I used the landscape mosaic created by urban development to study how spatial structure affected the habitat condition of this endangered species. I quantified the habitat classification characteristics appropriate for assessing the effects of land use change on the GCW. Using a Geographical Information System (GIS) and spatial analysis techniques, I investigated several parameters that influence the condition of GCW habitat in an urban matrix. Habitat patch size and pattern, habitat topographic position, and road density adjacent to existing habitat were examined for relationships to bird sightings. The results suggest that conservation planning should focus on maintaining the largest, most contiguous patches of GCW habitat and attempt to minimize road density in areas adjacent to GCW habitat.

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## INTRODUCTION

The Hill Country, or Balcones Canyonlands, region of Texas is a complex mosaic of biological diversity (Lyndon B. Johnson School of Public Affairs 1978). Geologic processes, topographic variations, strong regional climatic gradients, and overlap of several biogeographical regions interact to produce a rich assemblage of biotic communities in this area. Recognition of this unique ecological heritage brings with it the realization that species and communities of the Hill Country face increasing levels of habitat destruction, fragmentation, and isolation. One species threatened by the changing conditions is the Golden-cheeked Warbler (*Dendroica chrysoparia*).

Of 555 bird species known to occur in Texas (Texas Ornithological Society 1984), the Golden-cheeked Warbler (GCW) is the only one whose breeding range is completely contained within the state (Oberholser 1974). The GCW has been observed in 41 Texas counties in the eastern third of the Edwards Plateau and southeastern quarter of the Cross Timbers and Prairies ecological regions (Pulich 1976).

The Golden-cheeked warbler was emergency listed as endangered by the U.S. Fish and Wildlife Service (USFWS) May 4, 1990. The final rule listing the GCW as endangered under the Endangered Species Act (ESA) was published December 27, 1990. It was added to the Texas Parks and Wildlife Department's list of endangered species on February 19, 1991. The GCW has a USFWS recovery priority of 2C indicating a species with a high degree of threats; in conflict with construction or development projects; and a high potential for recovery (55 FR 53153).

Golden-cheeked warbler habitat consists of mixed old-growth Ashe juniper (*Juniperus ashei*) and oak woodlands. Ashe juniper occurs at all sites inhabited by GCWs and is often the dominant species (USFWS 1992). Composition of the habitat varies in tree density, relative importance of juniper and oaks, and associated species

(Pulich 1976, Kroll 1980, Ladd 1985, Wahl et al. 1990). GCWs prefer areas with a moderate to high density of trees and dense foliage usually at high levels (Kroll 1980, Wahl et al. 1990). The shedding bark of mature Ashe junipers provides critical nesting material (Pulich 1976) and the associated deciduous species are thought to provide essential foraging habitat (Kroll 1980, Sexton 1987, Beardmore 1994). Suitable habitat often coincides with steep canyon slopes or rugged terrain (Ladd 1985), possibly because these areas provide: (1) seepage and run-off favoring growth of deciduous trees for forage habitat, (2) greater protection from fires, and (3) lower likelihood of clearing due to higher cost (USFWS 1992).

Natural land cover patterns occur as a result of complex interactions between climate, soil, topography and biotic factors. The alteration of natural land cover patterns by humans through urbanization, agriculture, and forestry results in removal of the natural vegetation followed by replacement with managed systems of altered structure and pattern. The spatial relationships of the altered land cover can influence a number of important ecological and environmental phenomena (Krummel 1987). Many early efforts focused on quantification of landscape geometry at the level of individual patches within landscapes, e.g. patch area and interpatch distance (Milne 1988). However, natural boundaries are so complex that most techniques developed until recently detected only certain kinds of patterns.

New methods incorporating remote sensing, GIS and spatial analysis have made it possible to quantify complex boundaries and relate these patterns to underlying processes. For this study, several new spatial analysis procedures were assessed for their utility in characterizing fragmentation patterns. Benson (1990) attempted to calculate a fractal dimension of potential GCW habitat "patches" within larger GCW habitat "sites" and then correlate this parameter with presence or absence of GCWs, but he observed no clear relationship with this particular method. Other approaches analyzed regional differences in the landscape (Krummel 1987, Decola 1989, Turner 1990). Landscape components that were less influenced by humans

(e.g. hardwood forests) tended to be more complex in shape than those which received greater human influence (e.g. urban or agriculture lands). Thus, broad-scale topographic patterns and physiography may be reflected in the complexity of the landscape (Turner 1990). DeCola (1989) conducted a study of northwest Vermont and reported that forested regions had a different fractal dimension than managed agricultural lands. Agricultural lands tended to have more linear, Euclidean borders. Krummel (1987) measured the fractal dimension over a range of length scales to examine the anthropogenic and geomorphic processes which contribute to landscape patterns. He successfully contrasted differences in the scale of human and natural processes that produce spatial landscape patterns.

In this study the methods of Krummel (1987), DeCola (1989), Turner (1990) and Vogelmann (1995) have been adapted to explore relationships between landscape pattern and land use practice in Travis County, Texas. I analyzed the effects of historical land use practices on fragmentation pattern, patch geometry and habitat distribution and, to the extent possible, related these variables to GCW habitat condition.

Specific objectives were to:

1. Develop a spatial GIS database from historical photography and satellite imagery to quantify historical (past 40 years) and current habitat extent for nine study areas within the GCW distribution range in Travis County, Texas.
2. Calculate landscape spatial attributes (habitat patch area, shape and slope) and land use factors (urban/rural/recreational, density and proximity) which may influence GCW habitat.
3. Use various spatial analysis procedures to characterize habitat alteration patterns.

The five study hypotheses were:

1. Aerial photogrammetry, satellite remote sensing and ancillary GIS data could be used to monitor the fragmentation of GCW habitat within Travis County, Texas.

2. In study sites fragmented by urbanization, GCW habitat should be concentrated on steeper slopes. Conversely, in study areas unaffected by urbanization, GCW habitat should occur throughout the landscape.
3. Sightings of GCW should occur in equal proportion to their habitat availability, meaning that GCW sightings would not occur more often in steeper habitats.
4. Continuity index (CI, Vogelmann 1995) could be used to measure habitat fragmentation within study areas and provide a metric to compare patterns of land use between study areas.
5. Road density in former GCW habitat could be used to assess the condition of remaining habitat.

## LITERATURE REVIEW

The GCW is a small insectivorous bird. Adult males are about 15 cm long, black on the crown, nape, back, throat and breast. Adult males have brilliant yellow cheeks outlined in black. The face has a distinctive black eyeline. The wings are black with two white wingbars. The underparts are white streaked with black streaks on the flanks. Adult females are similar though duller, having paler cheek patches and eye stripe, and a greenish crown and back with some black-streaking (BAT 1990, USFWS 1992).

Mengel (1964) described a reasonable scenario for the derivation of the GCW from an ancestral form of the black-throated green warbler (D. virens). The GCW is thought to have separated from the ancestral stock during one of the Pleistocene interpluvial episodes about 20,000 years before the present. The validity of this scenario is supported by similarities in plumage, vocalizations, and habitat preferences of these species and Pleistocene vegetation distribution (USFWS 1992).

Pulich (1976) wrote the first comprehensive work on the life history and nesting ecology of the GCW. Generally, GCWs occupy their breeding territory in central Texas from mid-March to mid-August (USFWS 1992). The highlands of Guatemala, Honduras, Nicaragua, and Mexico serve as GCW wintering grounds where it has been observed or collected in pine-oak woodlands at elevations ranging from 1500 m to 2500 m (Pulich 1976, Kroll 1980). Little detailed information about the winter habitat is available, although Kroll (1980) described the habitat at one site in Honduras as structurally similar to nesting habitat. The variation in habitat characteristics throughout the winter range is unknown (Wahl et al. 1990).

Habitat destruction in the breeding range has accelerated since the initials surveys by Pulich (USFWS 1992). Oberholser (1974) discussed the three main causes of habitat loss: land development for agriculture use, housing development, and reservoir construction. Portions of the Edwards Plateau just west of the Austin-San Antonio corridor exhibit the largest and least fragmented patches of habitat, yet it



is in this region that the greatest rate of habitat loss is occurring due to growth and development (Wahl et al. 1990, Clark 1985). In western Travis County, a 40% loss in GCW habitat occurred in the ten year period from 1979 to 1989 (Wahl et al. 1990). Clark (1985) reported a 7.4% annual rate of change from woody vegetation to urban by comparing two satellite images (1973-1979) of the Austin area. Clearing of woody cover for urban development has two effects on the warbler habitat: (1) reduction of total habitat acreage and (2) fragmentation of larger patches into smaller ones. In Travis County, Wahl et al. (1990) have observed large continuous patches of habitat broken into smaller fragments for business development and housing. As urban fragmentation occurs Blue jays (*Cyanocitta cristata*) and Brown-headed Cowbirds (*Molothrus ater*) may have considerable effect on GCWs by excluding GCWs from areas of apparently suitable habitat in urban areas through nest predation (Engels and Sexton 1994, Pease and Gingerich 1989). Several authors (Pulich 1976, Kroll 1980, Ladd 1985) have stated that GCW territories are often bounded by an edge of different vegetative composition, such as a road, clearing or pasture, but this point of view is challenged by the belief that GCWs do best in large blocks of unfragmented habitat (BAT 1990, Wahl et al. 1990, Pease and Gingerich 1989).

Kroll (1980) and Ladd (1985) quantified vegetative characteristics of GCW habitat and made an estimate of the number of hectares required to support a breeding pair. Also, Ladd (1985) made useful comparisons to previous estimates of vegetation composition and breeding territory size. A summary of studies conducted in Travis County showed that the estimated territory required per breeding pair of GCWs varies from 1.9 to 2.7 ha/pair (Ladd 1985).

Most recent authors have indicated that the population numbers of the GCW are decreasing due to loss of suitable nesting habitat (Ladd 1985). Pulich (1976) noted that estimates of territory size of displaying males should not be used to extrapolate GCW population sizes over extensive areas of oak-juniper woodland. Such extrapolation is inappropriate because (1) GCWs and other wood warblers do

not always saturate extensive expanses of suitable habitat, (2) a large portion of displaying males in a given population may be unpaired, and (3) non-displaying, non-territorial individuals may comprise a large portion of a given songbird population. Pulich (1976) related GCW density with habitat quality to estimate total GCW breeding pairs at 7,815 in 1962 and 7,475 in 1974. USFWS (1992) applied an average density value to an estimate of total potential habitat to obtain a much different result: 18,486 pairs in 1962 and 14,750 pairs in 1974 (USFWS 1992). Wahl et al. (1990) used another method to estimate the number of GCW breeding pairs in 1990 to be between 2,266 and 7,527. The wide range of estimates exemplify the difficulty involved in accurately determining GCW population levels.

A high density of GCW habitat remains in western Travis County outside of Austin, Texas (Wahl et al. 1989, Shaw et al. 1989). Thus, preservation of sufficient habitat within Travis County is important to the welfare of the GCW (BAT 1990). Protection efforts have resulted in the purchase of 22,000 acres of GCW habitat in Travis County. In the early 1970's, the Travis Audubon Society acquired approximately 600 acres in Travis County specifically for protection of the GCW. This area has a high population of the GCWs (Pulich 1976). Current efforts by the Texas Nature Conservancy include purchase and preservation of available properties containing GCW habitat around Austin, Texas. Another protection effort under way in Travis, Burnet, and Williamson counties is the establishment of the Balcones Canyonlands National Wildlife Refuge by the USFWS. It is hoped that, in conjunction with surrounding areas, the new refuge can support a significant population of GCWs. The refuge has already purchased 14,100 acres and proposes to be at least 41,000 acres when completed (USFWS 1992).

Application of remote sensing technologies for the identification of potential habitat for the GCW has been successfully applied in previous studies (Shaw et al. 1989, Shaw 1989). In this study, as in previous remote sensing studies of GCW habitat (Wahl et al. 1990), habitat is narrowly defined to be specific set of vegetation

characteristics and should not be confused with broader definitions of habitat that may embody elements such as soil type, elevation or climate.

GIS has been an ideal tool for the study of threatened and endangered species in the Austin region and for the planning of a preserve system in accordance with the provisions of the ESA (Ludeke and Ladd 1991). A GIS allows the representation of spatially heterogeneous landscapes and fragmentation through time and to provide data for predicting probabilities of further decline. The GIS incorporates multiple data layers, their spatial structure and requisite attributes.

## STUDY AREAS

Located in a southern extension of the Great Plains Physiographic Province of North America, the Balcones Canyonland forms the eastern and southeastern portions of the Edwards Plateau of Texas (Shaw 1989). The climate of the region is subtropical-subhumid with mean annual precipitation of 80 cm/yr (Riskind and Diamond 1986) and an average July normal temperature of 85° F (Pulich 1976). The region is described as a hilly, heavily dissected area on the upthrust side of the Balcones Escarpment (BAT 1990). The geology of the region is dominated by sedimentary Cretaceous limestone. Exposed rocks are commonly composed of alternating beds of limestones and dolomites of varying thickness from the Glen Rose formation. Soil texture varies from loamy to clayey depending on substrate and amount of profile development (Shaw 1989). The vegetation community has been classified as a live oak-juniper association (McMahan et al. 1984). Ashe juniper often occurs on calcareous, shallow, rocky soils derived from limestone and dolomite substrates (Smeins et al. 1994). Common species include Ashe juniper, plateau live oak, Lacey oak, scalybark oak, Texas oak, cedar elm, Texas persimmon, black cherry, sumac, agarita, little bluestem, sideoats grama, Texas cupgrass, Texas wintergrass, Texas grama, buffalo grass, curlymesquite, purple threeawn, and hairy tridens (Riskind and Diamond 1988).

Historical records of vegetation and land use for the Balcones Canyonland region are sparse. Schmid (1969) provides a general summary for the Edwards Plateau. He described cattle grazing as a predominant land use beginning about 1870. Raising sheep became more preferred after the turn of the century. High stocking rates of both cattle and sheep continued through the 1930's and 1940's even though the negative effects of overgrazing were becoming pervasive, particularly in the form of woody plant encroachment into grasslands. Fire history is sketchy, but it is commonly believed that practices associated with intense livestock grazing reduced the occurrence of natural fires. Periodic fire may have been an important factor in

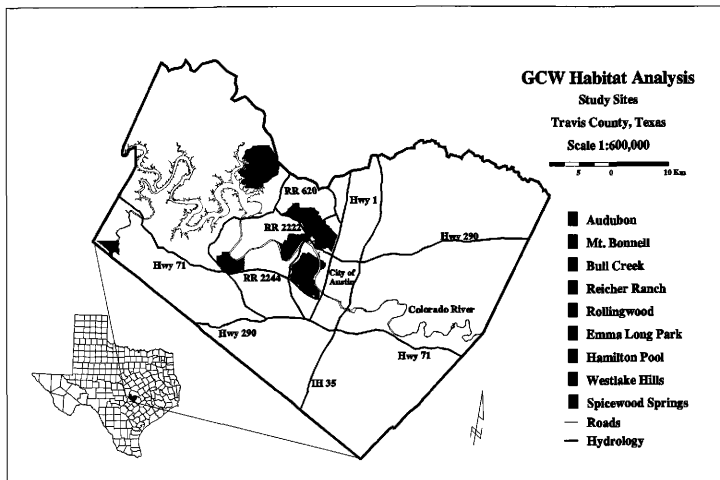
maintaining grassland areas and restricting the encroachment of woody plants, especially Ashe juniper (Schmid 1969).

Within the Edwards Plateau, nine study areas were located in western Travis County, Texas (Map 1). The nine sites were selected to permit analysis of a gradient of land use types ranging from urban to recreational to rural (Table 1). The sites were identified from discussions with experts knowledgeable about historical distribution of GCW habitat in Travis County, Texas. Three types of urban land use were represented. Low density urban was defined as residential housing developments that were predominately single-family dwellings on large lots ( $>2$  ha). Medium density urban contained a mixture of large lots and standard lots ( $<0.5$  ha). High density urban was dominated by standard lots. Recreational land use represented sites where a majority of the property was public park land designated for wildlife conservation or nature education. Finally, rural sites were areas which were located outside of Austin 'proper' (west of Loop 360) and contained only minor housing development.

## AUDUBON

At 3,420 hectares, the Audubon is the largest study site analyzed (Table 1). It is characterized by a patchy, broken appearance and dominated by the complex boundaries of several non-contiguous habitat islands. The extremely rough topography varies from 212 meters (above mean sea level) to over 320 m (Table 2). Several small streams and incised canyons criss-cross the site resulting in a wide array of habitat characteristics varying in both size, distribution and slope.

The Travis Audubon Sanctuary is completely contained within the study site, thereby providing a stable base of over 240 hectares of preserved lands. In terms of land use, the site exhibits only minor road development and low housing density. Indicating its relatively remote location from the City of Austin. Main threats to habitat condition arise from adjacent development around Lake Travis and urban expansion north of the site along U.S. Highway 183.



Map 1. Base map of nine GCW habitat analysis study sites in Travis County, Texas.

Table 1. Land use and size of nine study sites in Travis County, Texas.

Study Site Name	Type of Land Use	Study Site Size (ha)
Audubon	rural	3,420
Bull Creek	rural	1,655
Emma Long Park	recreational	1,202
Reicher Ranch	recreational	1,069
West Lake Hills	urban, low density	1,833
Rollingwood	urban, medium density	504
Spicewood Springs	urban, high density	1,393
Hamilton Pool	recreational	517
Mount Bonnell	recreational	93

#### BULL CREEK

Bull Creek (1,655 ha) is characterized by a large, nearly contiguous block of habitat (Table 1). The topography is dominated by three canyons. One is the main watershed for Bull Creek, another feeds Bull Creek and the other is a canyon stream which flow directly to the Colorado river. The undulating topography varies in elevation from 167 m to over 315 m within the study area boundary (Table 2). The site currently contains over 200 hectares of conservation lands and contains a low housing density overall. Emerging road development, a close proximity to major urban development along U.S. Highway 183, and continued expansion of residential housing in adjacent Spicewood Springs promote legitimate concern about future habitat condition.

Table 2. Elevational data (m) for nine study sites in Travis County, Texas.

Study Site Name	Elevation (m)				
	Minimum	Maximum	Difference	Avg.	S.D.
Audubon	212	320	108	275	27
Bull Creek	167	315	148	246	35
Emma Long Park	145	286	141	204	33
Reicher Ranch	147	319	172	238	40
West Lake Hills	139	302	163	217	32
Rollingwood	138	231	93	188	22
Spicewood Springs	167	274	107	229	30
Hamilton Pool	210	286	76	242	22
Mount Bonnell	143	260	117	200	20

#### EMMA LONG PARK

Representing 1,202 hectares, the Emma Long Park site consists almost entirely of Austin city park land (Table 1). The site exhibits a large, nearly contiguous block of habitat. The moderate topography includes several canyons which serve as watersheds for the Colorado river. The rolling landscape varies from 145 m to over 286 m within the study area boundary (Table 2). Some urban land use is localized in areas east of park boundary, the park's close proximity to emerging urban development along Highway 2222, and changes within nearby Westlake Hills are cause for concern.

#### REICHER RANCH

Covering approximately 1,069 hectares, the Reicher Ranch site contains property once owned by the Catholic Church that is now owned by the City of Austin (Table 1). The site includes some adjacent private land holdings as well. Flowing



toward the Colorado River, several small streams with steep canyon hillsides give the site a characteristic appearance as habitat identification essentially demarks the canyons borders. The uplands are non-habitat lands consisting of a shrub/grassland mixture while the canyons are full of large, mature junipers and oaks. Extreme topological change occurs at the site where the elevation varies from the southern uplands at 319 m elevation down through deep, tree-filled canyons to the Colorado River (elevation 147 m) at the north edge of the site (Table 2). This City of Austin property is essentially undisturbed with minimal construction or road building occurring over the course of the study, but housing projects are beginning to encroach on the eastern third of the study site as new suburban expansion continues along U. S. Highway 2244.

#### WESTLAKE HILLS

At 1,833 hectares, Westlake Hills is the second largest site (Table 1). Wild Basin Preserve, a county property, is located within the western edge of the study site. Westlake Hills is characterized by patchy, jagged boundaries of non-contiguous habitat islands. The extremely rough topography varies from 139 m to over 302 m within the study area (Table 2). Most of site is a highly desirable, low density (lot sizes often exceed several acres), but growing residential area. The area faces future pressures from bordering corridors of development including highway 360 and U. S. Highway 2244. Also, the site is adjacent to Rollingwood and across the river from Austin proper, both of which are major centers of urban development and growth.

#### ROLLINGWOOD

At 504 hectares, Rollingwood is one of the smaller sites (Table 1). The area does not contain any public conservation lands and is characterized by patchy, isolated habitat. Gently rolling hills dominate the area. The mild topography varies from 138 m to 231 m (Table 2). The site is a popular and growing residential area.

The site is surrounded by other urban growth and ongoing pressure to build on remaining open spaces exists.

#### SPICEWOOD SPRINGS

At 1,393 hectares, Spicewood Springs is a mid-sized site which contains portions of Bull Creek District Park (Table 1). The site is characterized by intense urban development resulting in the exclusion of habitat to just a few remaining patches in the western region. The topography varies from mild in the eastern half to steep canyon hillsides in the western half. The diverse topography varies in elevation from 167 m to over 274 m (Table 2). The site is another a highly desirable and growing residential area. The site faces ongoing threats from further urban expansion along its borders from the growth corridors of Highway 360, Highway 2222 and Highway 1.

#### HAMILTON POOL

Another small site at just 517 hectares, Hamilton Pool contains Hamilton Pool Park lands and West Cave Preserve (Table 1). The site is in a undeveloped rural area adjacent to the Pedernales River and is characterized by two canyon streams that flow into the main river channel. The moderate topography varies from 210 m to 286 m (Table 2). Minimal housing development and only minor road building has occurred within this recreational study area.

#### MOUNT BONNELL

At 93 hectares, Mt. Bonnell is the smallest site in the study (Table 1). It contains Mount Bonnell Park lands and surrounding residential properties whose housing density is intensifying. The steep topography varies from 143 m to 260 m (Table 2). Moderate road development and a high housing density have turned this site into an island of vegetation within a matrix of urban land.

## METHODS

GCW habitat was delineated using a combination of aerial photo-interpretation and satellite image classification for nine study sites at three reference points during the forty (40) year study. GIS was used to estimate habitat area and perimeter values in 1951, 1980, and 1991 after appropriate adjustments were made to compensate for inherent differences in photo-interpretation and satellite image classification methodologies. Changes in habitat area and patch shape were calculated. Area and perimeter values were used to calculate a patch continuity index (Vogelmann 1995). Habitat topographic position, GCW sighting data, and road density in former habitat were investigated.

## REMOTE SENSING/GIS ANALYSIS

Aerial photography and satellite imagery was used to delineate change through time in distribution of potential GCW habitat in the nine study sites within Travis County, Texas. All inferences about habitat occurrence were derived from analysis of the vegetation composition. Source data consisted of aerial photographs obtained from Texas Natural Resources Information System (TNRIS) and Landsat thematic mapper satellite imagery provided by the Texas A&M University Forest Science Department. Aerial photographs included Soil Conservation Service (SCS) panchromatic photos dated 1951 and Texas Highway Department (TXHD) panchromatic photos dated 1980. The Landsat satellite imagery was from 1991. Base maps were derived from five United States Geological Survey (USGS) topographical maps (Austin West, Austin East, Bee Cave, Pflugerville, Jollyville, and Mansfield Dam).

A Wild (Wild Heerbrugg Inc., Switzerland) magnifying stereoscope was used for all stereo viewing of photographs. GCW habitat distribution was marked on acetate sheets overlayed on the photographs and a Kail (Philip B. Kail and Assoc., Denver, Colorado) system was used to project photographic overlays onto USGS

base map overlays. Base maps were digitized into the ARC/INFO (ESRI 1990) geographical information system. Satellite data was processed using ERDAS (ERDAS 1992) image processing software and converted to ARC/INFO format.

Identification of vegetation composition was the fundamental data layer in habitat delineation. GCW habitat is characterized as mixed juniper-oak woodland. Warbler density has been positively correlated with increased mean stand height, increased variance in stand height, and increased cover of oaks (Wahl et al. 1990). Ashe juniper and numerous oak species such as Texas oak (*Quercus buckleyi*), live oak (*Q. fusiformis*), Lacey oak (*Q. glaucoides*) dominate the stand canopies. In the nine study sites within western Travis County, juniper-oak woodlands possessed distinct visual characteristics relative to surrounding vegetation. In panchromatic photos, the juniper was quite dark and distinguishable from intermixed oak species. Stands of closed canopy woodland in this region are predominantly a mixture of juniper and oak (Wahl et al. 1990), therefore identification of relative species composition and percent canopy cover was straightforward. Instead of having to identify subtle differences in vegetative cover, juniper-oak woodlands were easily distinguished from adjacent shrubland or urban areas. Juniper-oak woodlands were found on the hillsides, within valleys and in mildly sloped areas.

Defining the visual parameters that constituted a habitat patch was a key component of the photo-interpretation. The method required establishing a patch definition and a process for applying it. A habitat patch was defined as a cover vegetation type consisting of an Ashe juniper-deciduous species mixture with an approximated minimum canopy cover of 65% at 5.5 m (USFWS 1992). A wide variation in canopy and understory dominance by the juniper and deciduous species was considered reasonable (Wahl et al. 1990, Kroll 1980). During photo-interpretation, clumps of habitat separated by more than 25 meters were considered distinct patches. This amount of separation was chosen since it is analogous to the smallest amount of separation that satellite image classification techniques were

capable of detecting with the 1991 satellite data. This smallest resolvable unit, termed minimum pixel size, was 25 m by 25 m ( $625 \text{ m}^2$ ) for the satellite data used in this study. Also during photo-interpretation, clumps of juniper-oak woodland smaller than 50 m by 50 m ( $2500 \text{ m}^2$ ) were excluded from habitat designation. This exclusion of patches smaller than  $2500 \text{ m}^2$  was chosen to facilitate a process that could also be comparably implemented during satellite image classification. Using the defined patch criteria, a hierarchical land use classification was performed on each study area based on methods developed for remote sensing (Anderson et. al. 1976). In this method of classification, land cover is considered a surrogate to land use. Major categories in the classification were GCW habitat, urban land and other (agricultural, rangeland, and barren land). Identification of a land cover type was believed to be sufficient information to assign a land use designation. This systematic process was followed in all nine study areas to ensure that habitat and non-habitat areas would be consistently identified. Photo-interpretation is largely a deductive process, so analysis proceeded from the general to the specific. The following steps were followed after the photography was assembled and organized:

1. Major transportation routes and water courses were marked.
2. Park/recreation areas were marked.
3. Habitat patches were marked.
4. Areas were outlined that had urban characteristics.
5. Commercial subareas were marked.
6. Urban areas were divided based on differences in street patterns.

Study site locations were determined through collaboration with staff of the U.S. Fish and Wildlife Service, Texas Parks and Wildlife and Nature Conservancy biologists. The identified sites included regions currently utilized by GCWs as well as sites known for historical occurrence of GCW. Three of the study areas were used as test sites to confirm that stereographic interpretation of the aerial photos could reliably identify GCW habitat in this region of Texas. The three study areas chosen for the trial were Spicewood Springs, Westlake Hills and Reicher Ranch. During the

spring of 1993, trial habitat delineations were performed utilizing the 1951 and 1980 photographs.

Results were compiled on acetate overlays of USGS topographic maps. Several hours were spent at each site during the summer of 1993 to confirm that the photo-interpretation delineations were a reasonable representation of study site vegetation composition and associated land use. Field verification of historical photography is inherently challenging because changes in landscape composition have usually occurred since the photographs were taken. During the site visits, I found a consistent agreement between the habitat delineations and landscape structure. It was only in situations where recent urban expansions were evident that I was unable to reasonably confirm habitat delineations. Consequently, the same land use classification system and photo-interpretation methods were applied to the remaining six study sites.

A classified satellite image of GCW habitat in Travis County, Texas was made available for use in this study through a Golden-cheeked Warbler-GIS Section 6 Project cooperatively supported by the U.S. Fish and Wildlife Service, Texas Parks and Wildlife Department, and the Texas A&M Forest Science Department. For interpretation of the satellite imagery, habitat locations mapped on 7.5' USGS quadrangles by Texas Parks and Wildlife Department personnel were used to identify a representative spectral signature of GCW habitat within the satellite image scene. The entire satellite image was subsequently processed using the verified spectral signature to delineate GCW habitat (McKinney 1994).

Base map overlays of habitat delineations derived from the photo-interpretation of aerial photographs and the processed satellite imagery were input into a GIS. Roads, hydrography, railroads and pipeline layers were assembled from TIGER/Line file (Bureau of the Census, Washington 1988). GCW sighting data from FWS annual permit reports (DLS Associates, 1994) were combined with other GIS data layers.

The Mount Bonnell site exemplified a limitation in the methods employed to identify habitat. Initial analysis indicated that a substantial loss of GCW habitat occurred from 1951-1980, but upon closer inspection, it was determined that significant spatial distortion was evident in the source photographs. Aerial photographs contain the least amount of spatial distortion at their center. Unfortunately, the Mount Bonnell study site was not located in the center of the source photographs in 1951 and 1980, but at the outer margins. The distortion is compounded by the extreme topographical variation which occurs at the site. The photo-interpretation methodology can compensate for the reasonable levels of distortion normally associated with aerial photographs through the use of ground control points and use of the Kail projection system, but the distortion exhibited at the Mount Bonnell site was so severe that overlays of the 1951 and 1980 could not be reliably performed. Subsequent combination of the 1991 satellite imagery with the 1980 data showed a total lack of agreement between 1980 photographic habitat interpretation and 1991 image classification of habitat. Attempts to overlay road data from a TIGER/Line file was also unsuccessful due to conflicts in spatial alignment. The reasons for poor correlation of the 1991 satellite image data may be due to inaccuracies in control points or USGS base map, lack of GCW sighting data needed to create an accurate reflectance signature for image classification analysis, or dramatic relief which creates difficulties for image rectification and classification. The limitations of the study site data precluded further analysis of results for Mount Bonnell.

#### HABITAT/LAND USE ANALYSIS

After the assembly of a GIS, five (5) spatial analysis procedures were applied to study the effects of differing land use practices on GCW habitat. The processes quantified: 1) habitat loss and patch size change, 2) habitat slope relationships, 3) habitat use, 4) habitat Continuity Index, and 5) road density in former habitat.

### *Habitat Patch Size Change*

The GIS was used to estimate the size of the nine study sites (Map 1, Table 1). The outer perimeter of each study site had been agreed upon through consultation with Carol Beardmore of USFWS and were most often bounded by major roads, property lines, or landscape features such as cliffs, ridges or watercourses. After habitat classification by remote sensing methods, estimates of habitat extent in each of the study sites was determined for the three reference years (1951, 1980, and 1991). Satellite image classification procedures used to identify GCW habitat in 1991 intrinsically differed from photo-interpretation methods used to delineate GCW habitat for years 1951 and 1980. Satellite image classification relied on a strict set of computer algorithms to identify GCW habitat compared to the more adaptive pattern recognition skills of a human photo-interpreter. Some of the expected differences in GCW habitat identification resulting from the use of satellite imagery include: 1) over-estimation of habitat area arising from inclusion of immature juniper/oak woodlands, 2) under-estimation of habitat area due to the spectral reflectance of juniper/oak woodlands being 'washed out' by adjacent barren or sparsely vegetated land. Comparisons of GCW habitat delineations for 1980 photo-interpretation and 1991 satellite image classification indicated that the satellite image classification had a tendency to include young (less than ten years old) juniper/oak woodlands that often grew along the outer borders of established stands. To compensate for this over-estimate of GCW habitat, estimates of 1991 GCW habitat were adjusted by excluding juniper/oak vegetation that was identified as being less than ten years old. GIS algorithms (ESRI 1990) were then used to calculate the amount of habitat area lost and/or gained during the 40 year study period.'

To detect changes in habitat patch size distribution, an average habitat patch size was calculated. For each study site, the total habitat area and the number of



habitat patches was determined with GIS and an average patch size was calculated for 1950, 1980, and 1991.

#### *Habitat Topographic Position*

With a method similar to determining an animal's habitat preference (Neu et al. 1974), I explored the 'preference' that GCW habitat had for various topographic types in terms of their availability. In order to relate topographic variation of each site to available habitat and use by GCW's, a Digital Elevation Model (DEM) was utilized. The DEM is a digital cartographic file distributed by the U. S. Geological Survey (USGS). It consists of a sampled array of elevations for a number of ground positions located at regularly spaced intervals within a geographic (latitude/longitude) coordinate system (USGS 1993). The DEM used in this study was produced for USGS by the Defense Mapping Agency (DMA) and corresponds to a series of 1 degree by 1 degree map blocks (one half of standard 1:250,000-scale 1 degree x 2 degree quadrangles). This type of data is available for most of the United States and is referred to as 1:250,000-scale DEM data. Higher resolution 1:24,000 DEM data was not available from USGS at the time this study was performed. The lower resolution 1:250,000 DEM reduced the capability to precisely detect topography since elevations were sampled at greater horizontal intervals. The 1:250,000-scale DEM data are produced by interpolating elevations at intervals of 3 arc-seconds from contours, ridgelines, and drains digitized from 1:250,000-scale topographic maps (Elasall 1983). For Travis County, three arc-seconds represents approximately 90 meters in both the north-south and east-west axis. The accuracy of digital elevation models is partially dependent on the scale of the source materials from which data are obtained. The accuracy of the 1:250,000-scale DEM's is consistent with the accuracy of the contours (15 m in flat terrain, 30 m in moderate terrain, and 60 m in steep terrain) found on the 1:250,000-scale topographic maps used to produce the data.

The DEM's have been edited and modified by DMA to insure positional consistency with planimetric data categories such as hydrography and transportation.

DEM data describing elevation and aspect were combined with the digital map layers. Study site slope values were grouped into seven slope code categories (numbered 1 through 7) covering inclines from zero to 90 degrees ( $0-1^{\circ}$ ,  $1-2^{\circ}$ ,  $2-4^{\circ}$ ,  $4-8^{\circ}$ ,  $8-15^{\circ}$ ,  $15-30^{\circ}$ , and  $30-90^{\circ}$  respectively). The DEM provided the slope for all ground surfaces throughout the study site. The *available* proportion of each land cover type occurring in the seven slope categories was calculated. Then the habitat coverage was overlayed on the digital elevation model to determine the proportion of habitat *actually* occurring in each of seven slope categories. Bonferroni simultaneous confidence intervals were then calculated for this proportion of habitat actually in each slope category (Neu et al. 1974, Byers and Steinhorst 1984). With Bonferroni statistics, comparison of these two proportions of 'what is available' to 'what is actually there' allows a quantitative method of determining if habitat really does occur more often on steeper ground.

#### *GCW Habitat Use*

Endangered Species Permit annual reports submitted to the USFWS contained results from observational surveys conducted in potential GCW habitat. The surveys followed a standard USFWS protocol (Minimum Procedures for Determining the Presence/Absence of Golden-cheeked Warblers and Black-Capped Vireos, USFWS, Austin Ecological Services Office, Austin, TX). Georeferenced GCW sighting data were collected between 1990 and 1992 as part of USFWS permit reports (DLS Associates 1994). To investigate GCW habitat preference, GCW sighting data collected for the USFWS were overlayed onto the habitat maps using GIS.

Use of a given habitat in terms of its availability can be statistically determined using a chi-square test (Ostle 1963). The test is based on the hypothesis that animals

use habitat in proportion to their availability. The chi-square test does not determine use of individual categories, so additional statistics, known as Bonferroni normal statistics (Miller 1966), are used. For the multinomial distribution, individual confidence intervals are constructed for each theoretical proportion of occurrence in order to determine whether expected values were within the range of the significant effects. Constructing Bonferroni confidence intervals is required because when estimating two or more parameters simultaneously, the probability that any one interval estimate is incorrect increases (Neu et al. 1974). The increase is partially dependent upon the number of simultaneous estimates being made (Hopkins and Gross 1970). The resulting Bonferroni confidence intervals are slightly wider for each of the multiple estimates than for an estimate of only one parameter.

The working hypothesis was that GCW utilize habitat within each topographic category in exact proportion to its occurrence at the study site. The proportion of each topographic category for the study area and the number of GCW sightings within each topographic category were determined. Bonferroni statistics were then calculated to examine comparisons between estimated and expected occurrence to detect preference of individual topographic categories (Neu et al. 1974, Byers and Steinhorst 1984).

### *Continuity Index*

A Continuity Index (CI, Vogelmann 1995) was calculated to assess the spatial configuration of the habitat for the reference years of 1951, 1980 and 1991. Habitat area-perimeter ratios were defined for each site as the total area ( $m^2$ ) of all habitat polygons divided by the total length (m) of all habitat polygon perimeters. A CI was calculated for each site by taking the natural logarithm of the area-perimeter ratio ( $CI = \ln[\text{Area/Perimeter}]$ ). Assuming the edge complexity or fractal dimension (Milne 1988) does not change radically, the resulting CI values relate directly to the degree of habitat fragmentation. By this method, a fragmented site would exhibit a lower

CI, while a site with more intact and contiguous habitat blocks would have a higher CI (Figure 1).

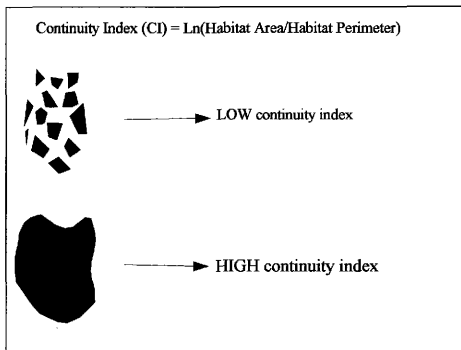


Figure 1. Relationship of continuity index (CI) to fragmentation level.

Dissimilar interpretation methodologies for aerial photography and satellite imagery produce inherent differences in delineation of habitat boundaries. Smoothing of complex edges is intrinsic to the visual identification of habitat boundaries used with photographic methods and resulted in a conservative estimate of habitat perimeter lengths. Software processing of the imagery over-estimated perimeter lengths because of the inherent geometric constraints of raster data (i.e. land cover information is represented by 25m square pixels). Also, limitations in GIS algorithms for converting raster imagery to the required vector format produce further perimeter distortions. Therefore, it was not productive to directly compare habitat fragmentation without normalizing habitat perimeter estimates to a common metric (Loehle 1994). When analyzing forest fragmentation in southern New England,

Vogelmann (1995) addressed a similar problem when comparing multispectral data from 1973 and 1988 derived from two different satellite sensor platforms. He selected a subset of data that contained only study sites that had undergone minimal change in land-cover condition (those that had approximately the same percentage of forest area in 1973 and 1988). The data subset represented the “no change” baseline condition. Using baseline data, he then regressed 1988 CI values against 1973 CI values and used the residuals to depict the level of change in the remaining study sites. I chose a similar normalization method. From 1980 to 1991, two study areas (Bull Creek and Emma Long Park) showed only minor changes in habitat area and underwent minimal change in road density, but the two sites exhibited a near doubling in perimeter estimation because of differences in interpretation methodology. Both study sites indicated similar magnitudes of perimeter adjustment would be required for normalization, but Bull Creek was chosen as the baseline condition due to its slightly larger size and wider mix of land use categories. Between 1980 and 1991, the habitat area of Bull Creek changed 1% while habitat perimeter length changed 52%. Based on Bull Creek, 1991 habitat perimeter estimates for all study sites were normalized by reducing perimeter lengths by 52%. The resulting perimeter lengths were used in calculating CI values to depict change in habitat fragmentation for each of the sites

### *Road Density*

Systematic remote sensing methods correlate higher road densities with greater levels of urbanization (Avery and Berlin 1992). Several methods of calculating road density were considered: 1) road density based on the total area of each study site, 2) road density based on a buffer around each habitat patch, and 3) road density based on former habitat area. The subjective establishment of study site boundaries resulted in a wide range of study site sizes and shapes. Also, pre-existing land uses and the proportion of each study site which was GCW habitat in 1951

varied. For these reasons, site-to-site comparisons of road density based on the total area did not provide much useful information. Road density based on a buffer around each habitat polygon was discounted because the buffers would extend beyond the study site boundaries into regions where GCW habitat existence and road networks were unknown. Calculation of road density in former GCW habitat was chosen for the following reasons: 1) the method is comparable from site to site, 2) source data for the calculations is contained within the study site boundaries, and 3) it provides a way to synthesize the study of habitat loss and urban development. Using GIS, the road density in former habitat was analyzed by examining regions within each of the study sites that were identified as habitat in 1951, but were subsequently urbanized by 1991. TIGER/Line files (US Bureau of the Census, 1990) provided the linear length of roads occurring in former habitat. Road density was calculated by dividing the total linear length of roads existing in former habitat by the total amount of habitat area lost.

## RESULTS

### REMOTE SENSING/GIS ANALYSIS

Overall, the quality of the aerial photographs was acceptable with only minor focal and contrast limitations. Quality of the 1951 SCS panchromatic photos (approximate scale 1:16,000) was only fair. Focus was a little fuzzy, due mainly to a 'grainy' appearance (Under high magnification, the fibers of the photo backing could be seen wearing through the photographic media). The tonal contrast was too light which made some brighter objects appear washed out. The 1980 TXHD panchromatic photos (approximate scale 1:24,000) were also of fair quality. Focus was not optimum and tonal contrast covered a small range of the gray scale. In a few minor cases, missing photography prevented complete stereo coverage. These concerns are the primary limitations to the accuracy of the photo data layers.

Methods of habitat delineation by stereographic interpretation of aerial photographs for the years 1951 and 1980 were intentionally conservative in the amount of immature juniper/oak woodlands classified as potential habitat. As the photographs were viewed with the stereoscope, a conscious effort was made to be careful and deliberate in identifying, as GCW habitat, only those vegetation types that possessed the proper characteristics. Since satellite image classification relies on computer algorithms instead of the pattern recognition abilities of a human photo-interpreter to perform the analysis, it was not possible to emulate the same conservative habitat classification methods when analyzing the 1991 satellite data. Initial 1991 habitat delineation for the Audubon, Emma Long Park, Reicher Ranch and West Lake Hills study sites showed increases in potential habitat from 1980 to 1991, but a closer review of the 1980 photographs indicated that the increase shown for 1991 was due in large part to the inclusion of young (less than ten years old) juniper/oak woodlands. The image classification methodology was unable to spectrally separate the older woodlands from the immature juniper trees that often grew along the outer borders of established stands. Compared to the satellite

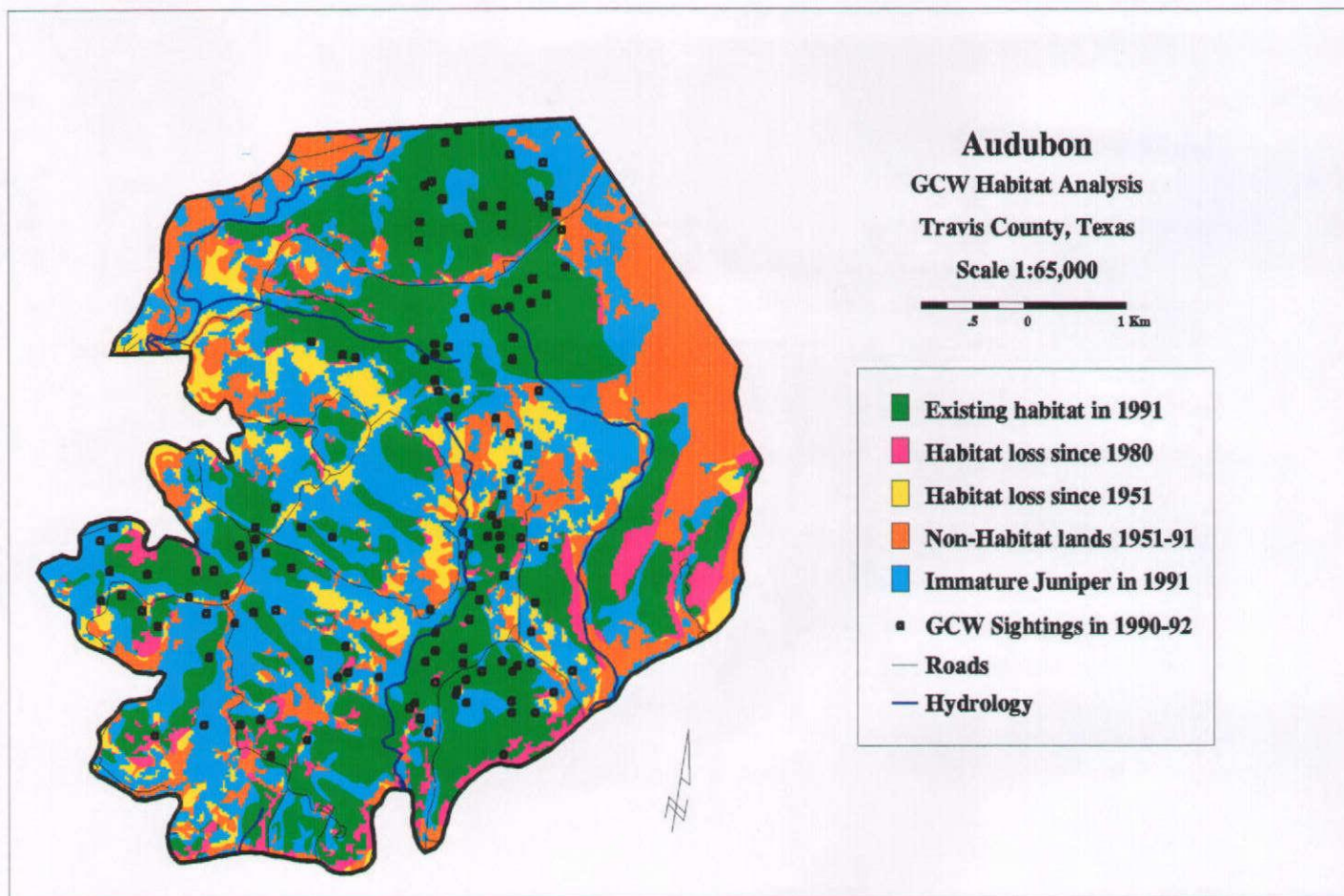
classification, a photography-based evaluation of the study sites in 1991 would likely result in a lower estimate of potential habitat due to the enhanced ability of photo-interpretation methods to discriminate tree height and species composition at the margins of woodland patches. Following consultation with FWS staff, juniper/oak vegetation that was identified in 1991 as being less than ten years old was excluded from the 1991 estimates of GCW habitat area. The adjustments were based on comparisons with 1980 aerial photography and resulted a reduction in estimated GCW habitat for Audubon of 1098 ha (48.6%), Emma Long Park of 111 ha (12.5%), Reicher Ranch of 220 ha (34.3%) and West Lake Hills of 285 ha (24.9%). Field verification of this adjustment was not performed.

Analyzing the habitat distribution through time was complicated by the temporal spacing of the photography. The leap of almost thirty years from 1951 to 1980 was difficult to compare to the eleven year span to the 1991 satellite imagery. Also, the mixing of photography-based and satellite-based classification methods introduced several complexities. Both classification methods have their respective advantages and short comings. Photographic interpretation provided a strict delineation of mature habitat, while satellite image classification methods included more young, marginal areas. The marginal areas were adjacent to older, more established woodlands, but the status of GCW using these immature woodlands for breeding or post-breeding dispersal is unknown.

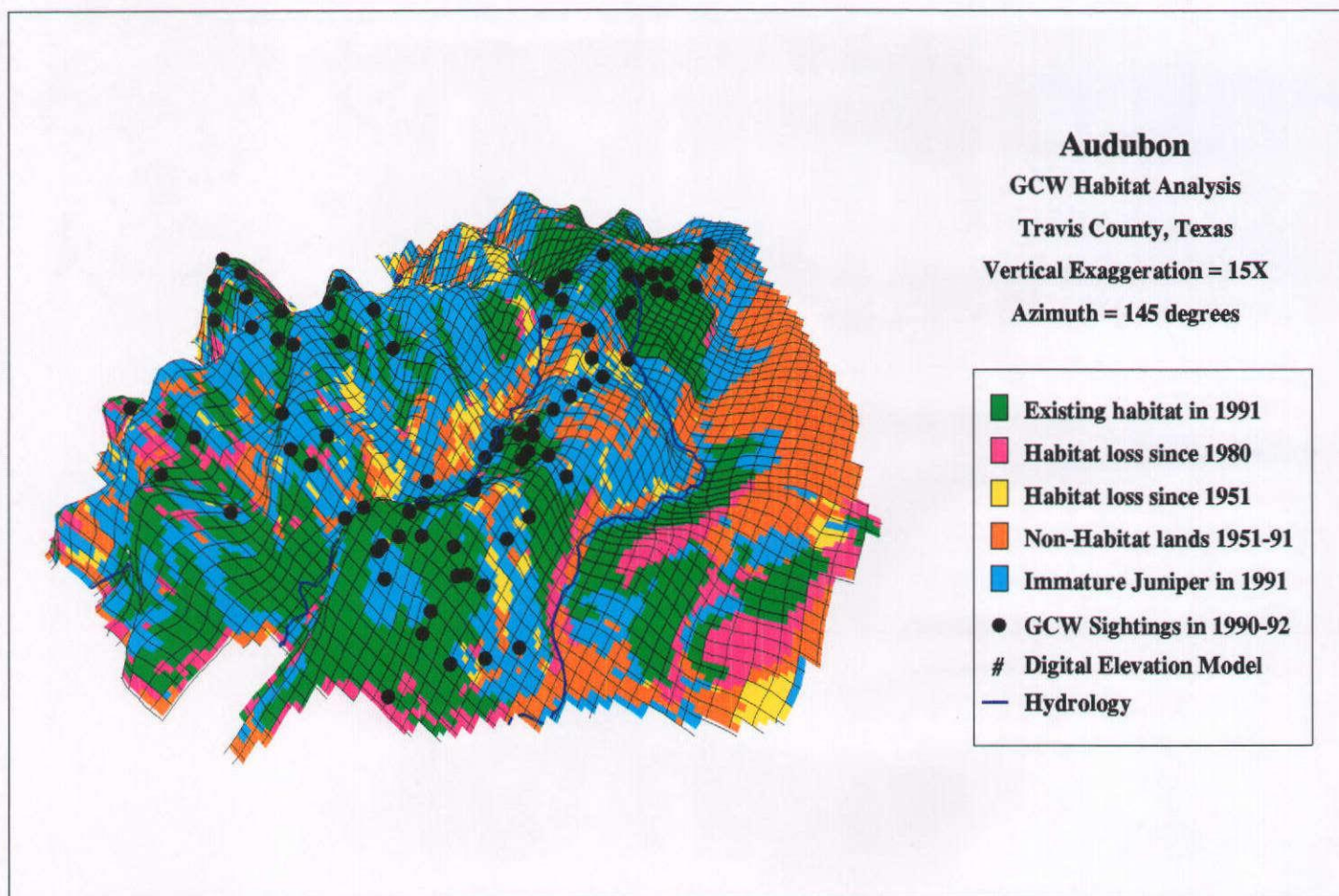
## GIS MAPS

Map 1 is a base map of Travis County and identifies the location of each study site. Two detailed GIS maps of each study site were prepared (Maps 2-17). Planimetric representations of the study sites are provided in Maps 2, 4, 6, 8, 10, 12, 14, and 16 to depict an undistorted view of habitat size, shape and loss. Maps 3, 5, 7, 9, 11, 13, 15, and 17 are commonly called 2 ½-D plots. They are visualizations intended to present a three-dimensional view on a two dimensional page.



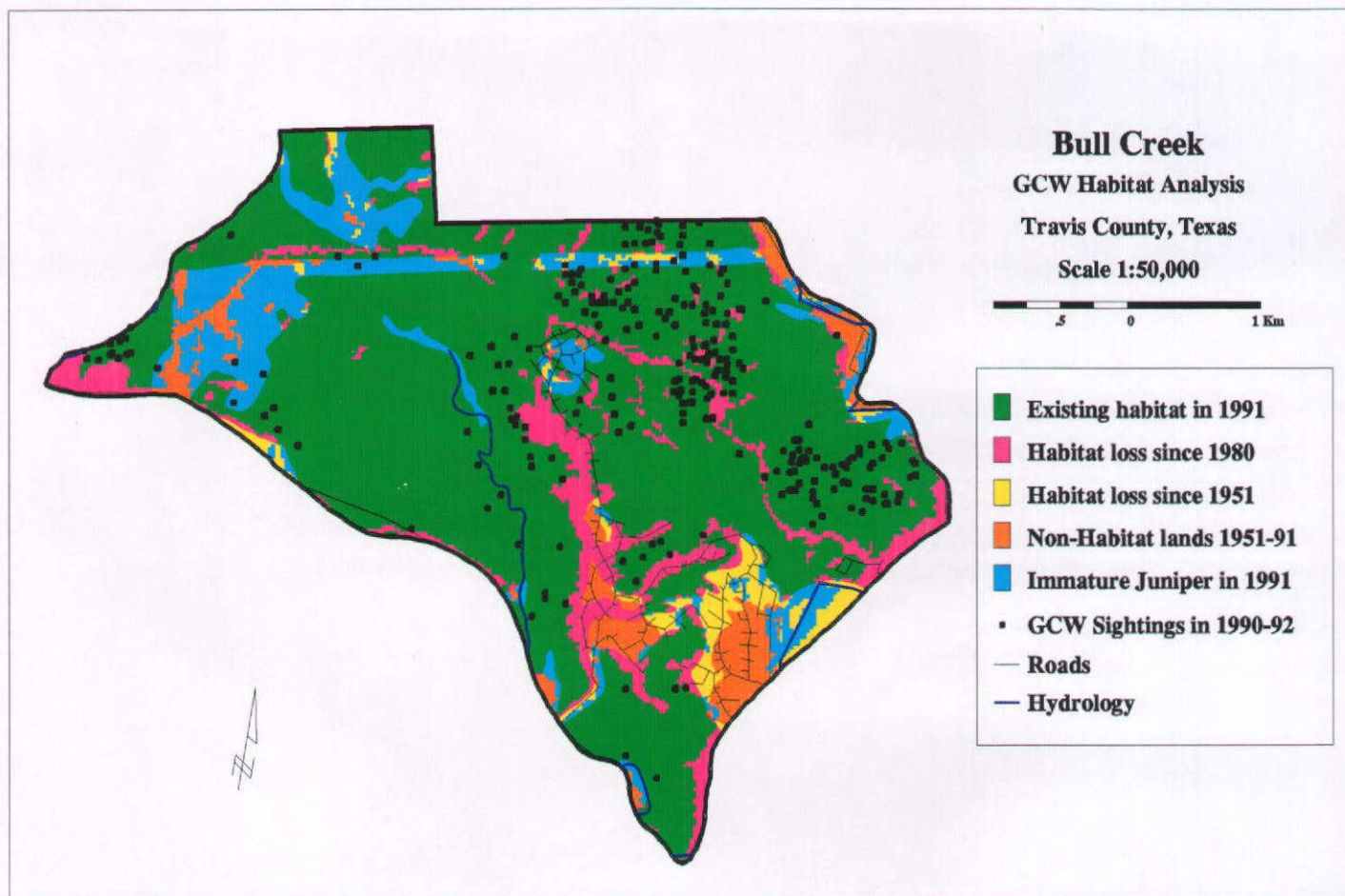


Map 2. Status of GCW habitat in Audubon study site for years 1951, 1980, and 1991 with 1990-1992 GCW sightings and 1988 road networks.

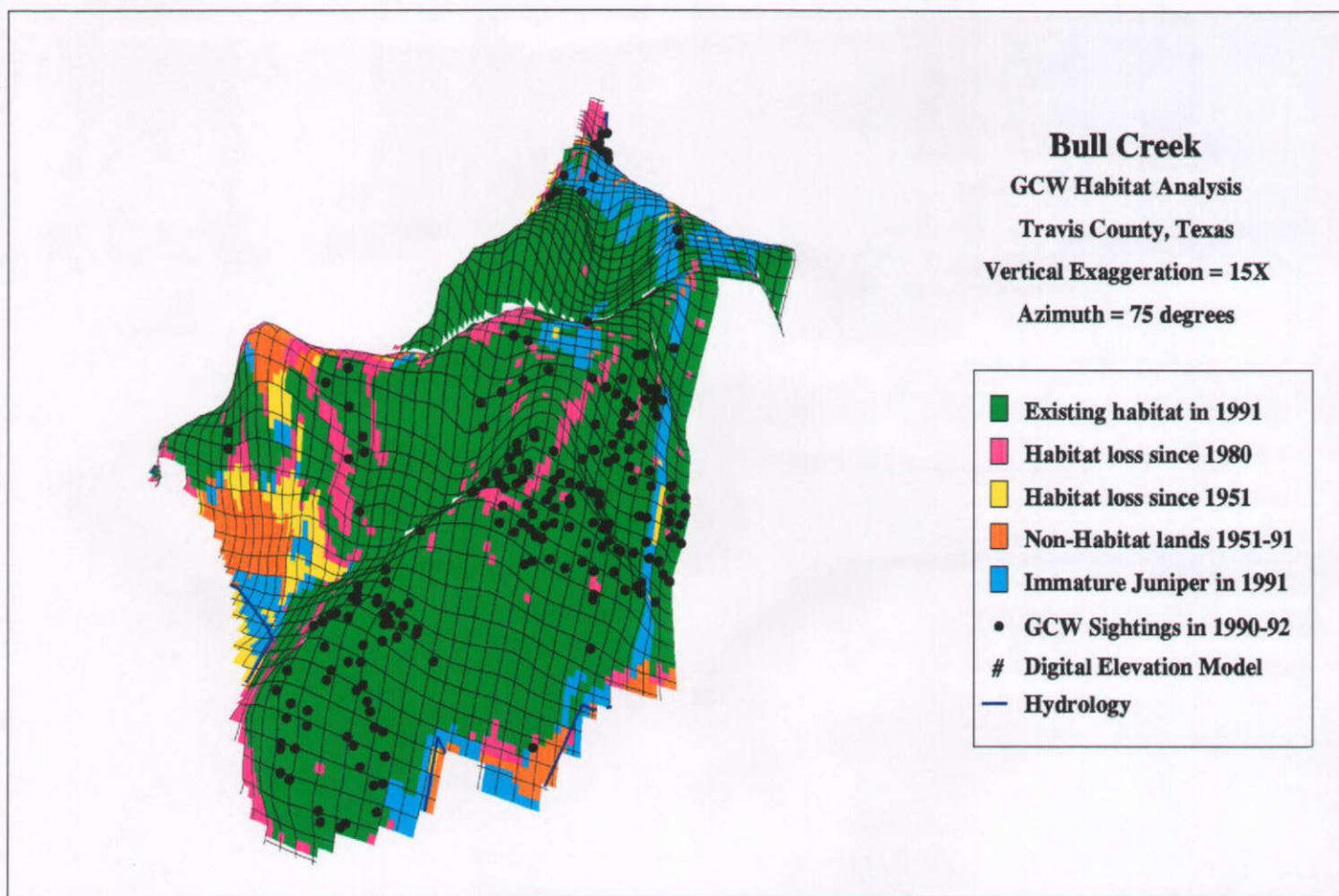


Map 3. Digital Elevation Model portraying topographic position of GCW habitat for the Audubon study site.

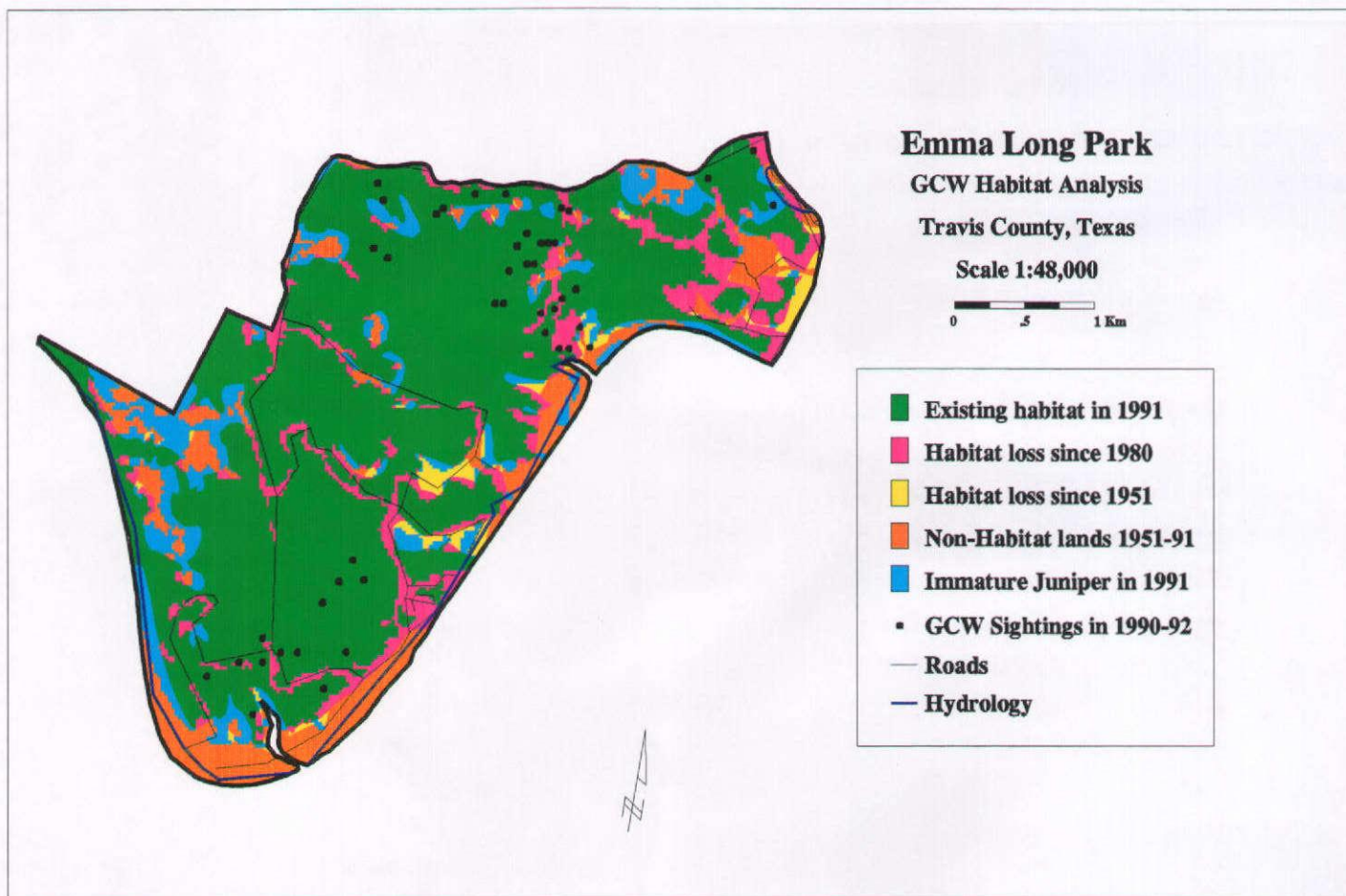




Map 4. Status of GCW habitat in Bull Creek study site for years 1951, 1980, and 1991 with 1990-1992 GCW sightings and 1988 road networks.

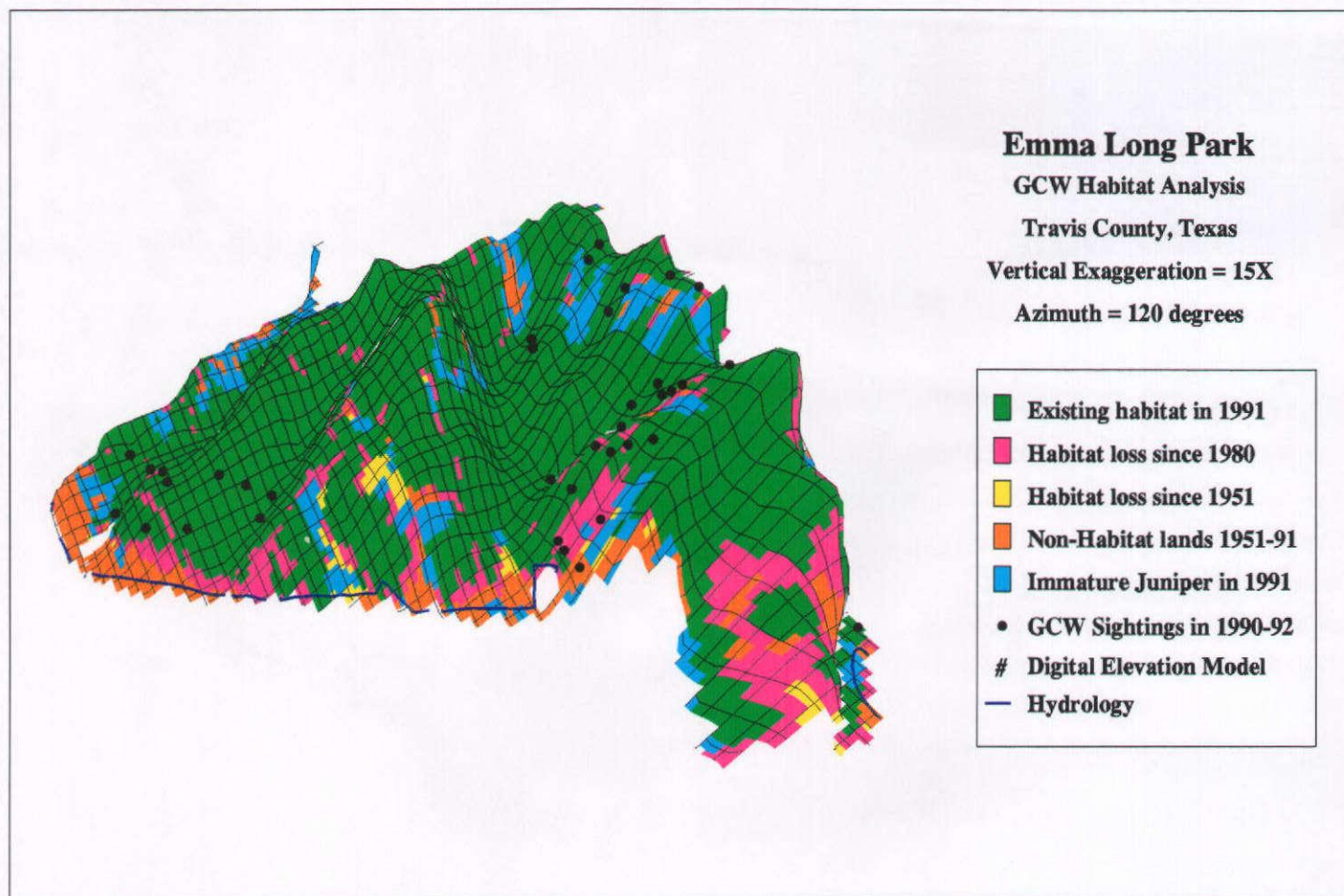


Map 5. Digital Elevation Model portraying topographic position of GCW habitat for the Bull Creek study site.

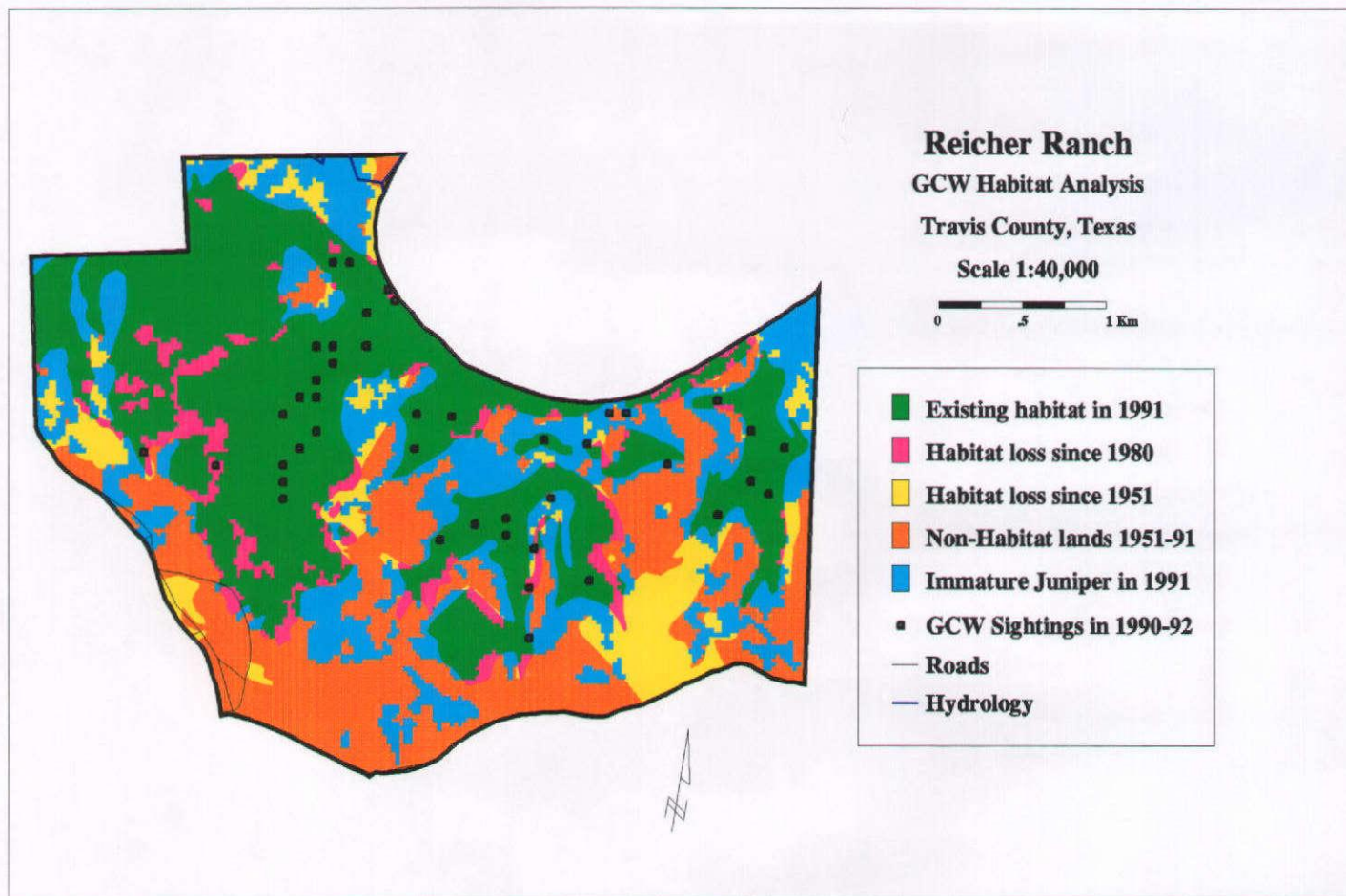


Map 6. Status of GCW habitat in Emma Long Park study site for years 1951, 1980, and 1991 with 1990-1992 GCW sightings and 1988 road networks.



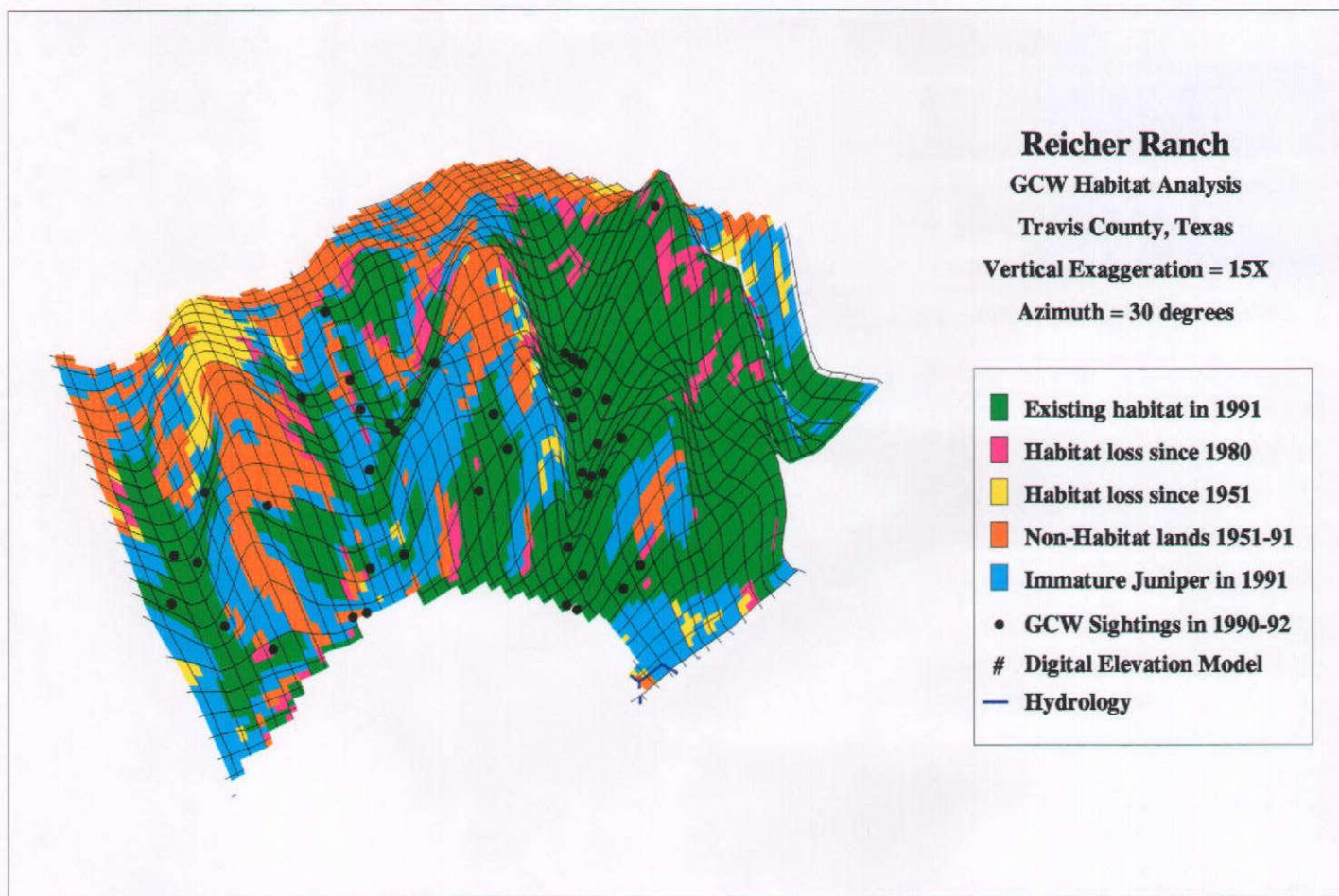


Map 7. Digital Elevation Model portraying topographic position of GCW habitat for the Emma Long Park study site.



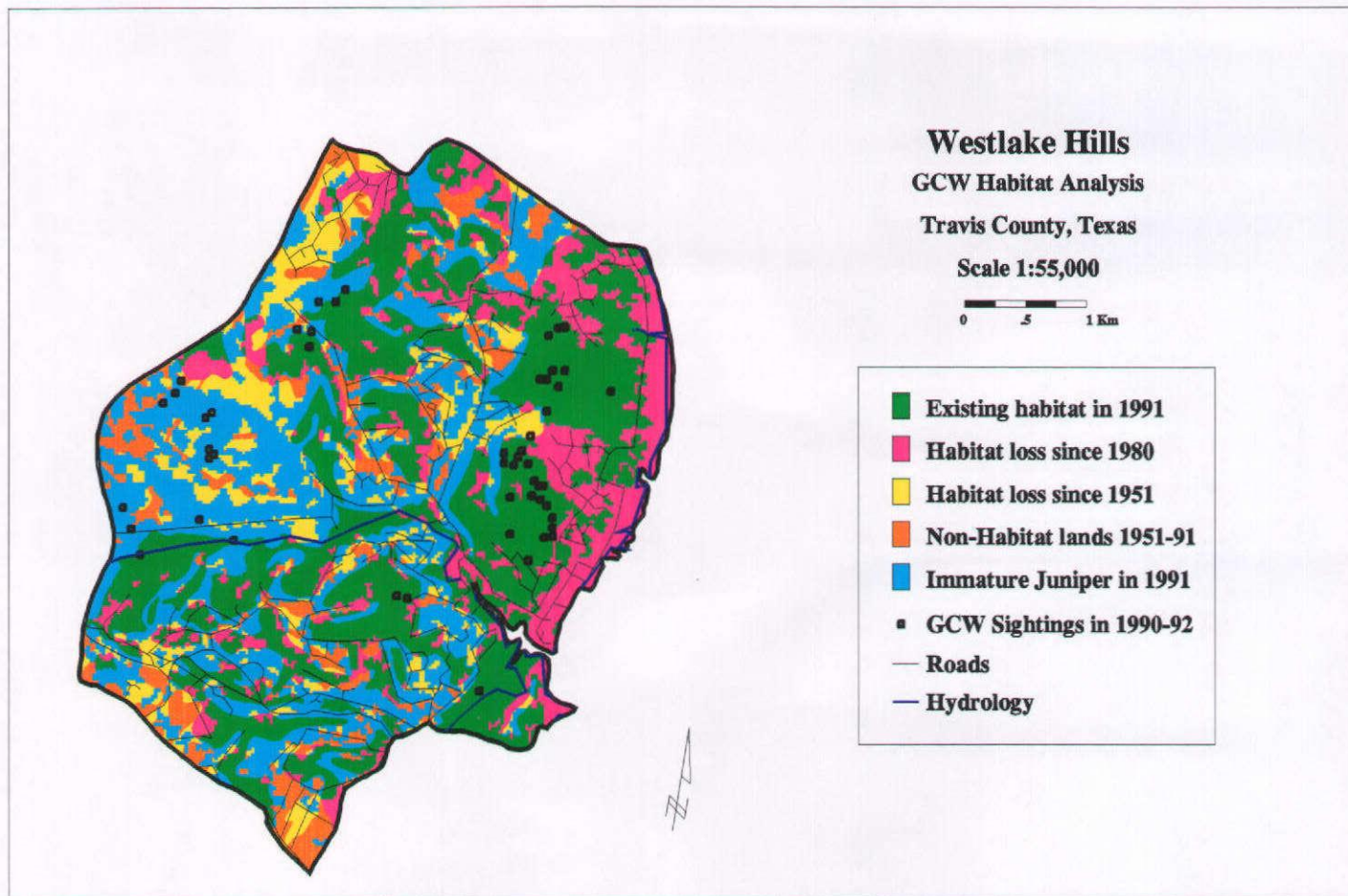
Map 8. Status of GCW habitat in Reicher Ranch study site for years 1951, 1980, and 1991 with 1990-1992 GCW sightings and 1988 road networks.



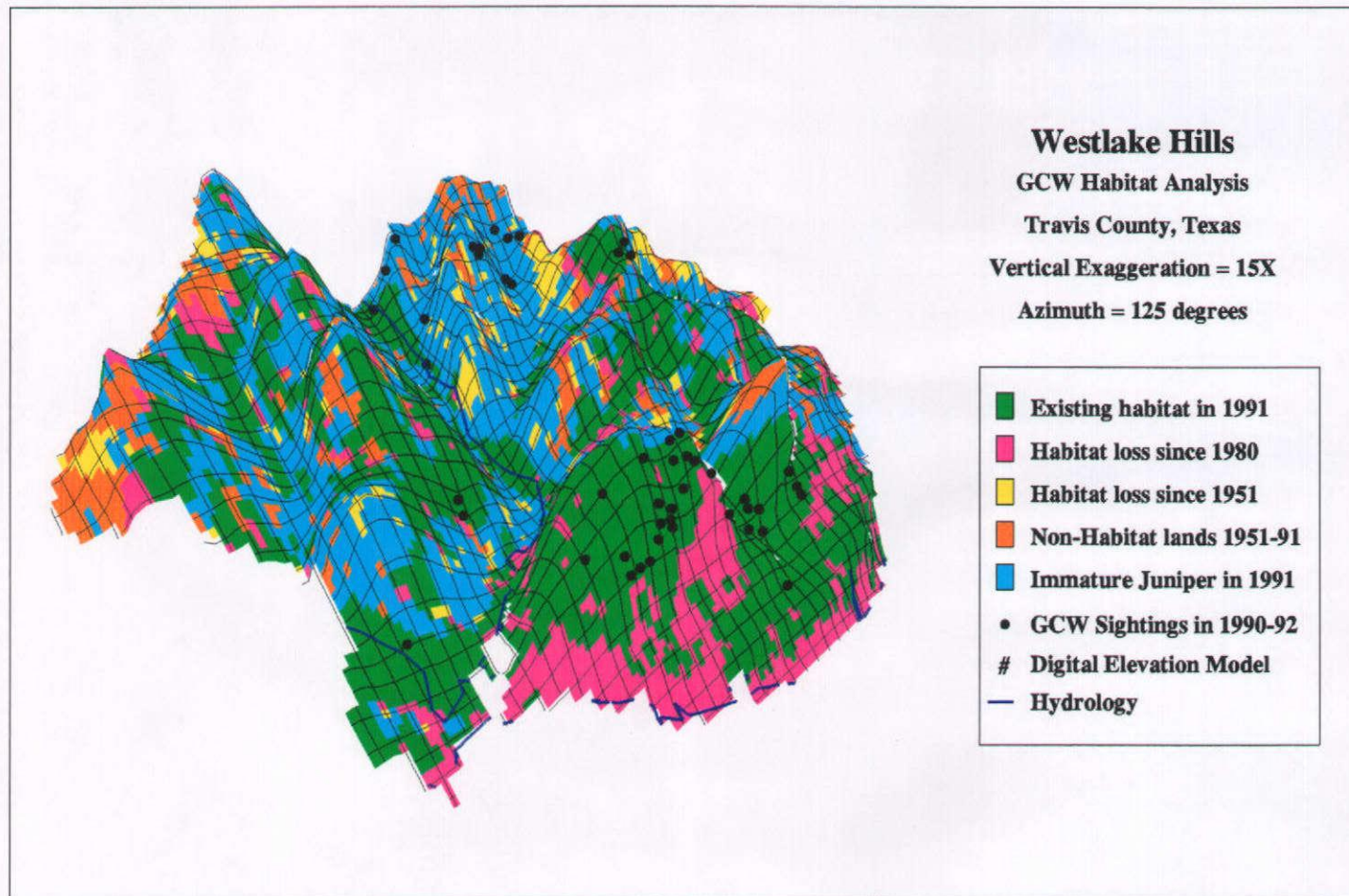


Map 9. Digital Elevation Model portraying topographic position of GCW habitat for the Reicher Ranch study site.



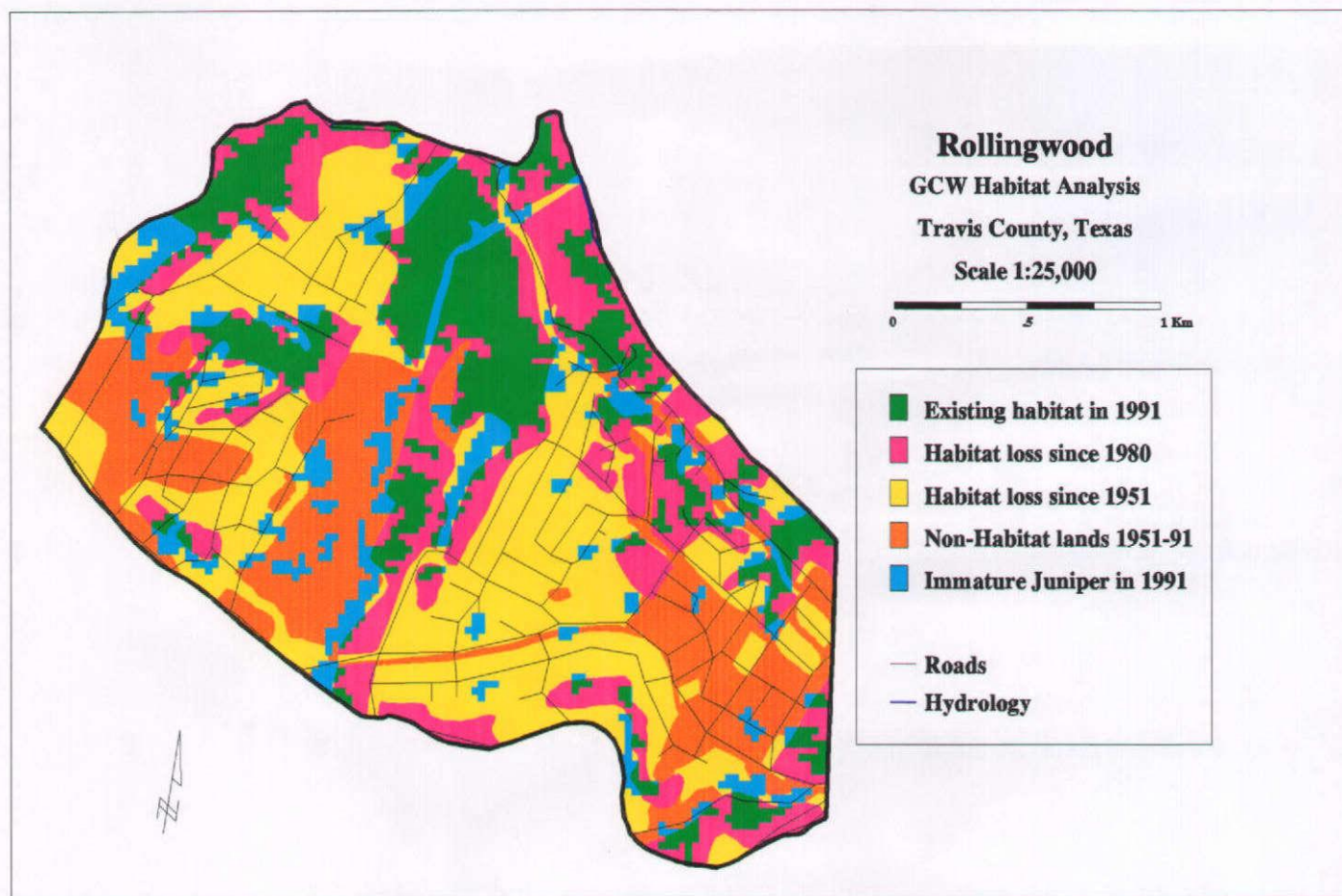


Map 10. Status of GCW habitat in Westlake Hills study site for years 1951, 1980, and 1991 with 1990-1992 GCW sightings and 1988 road networks.

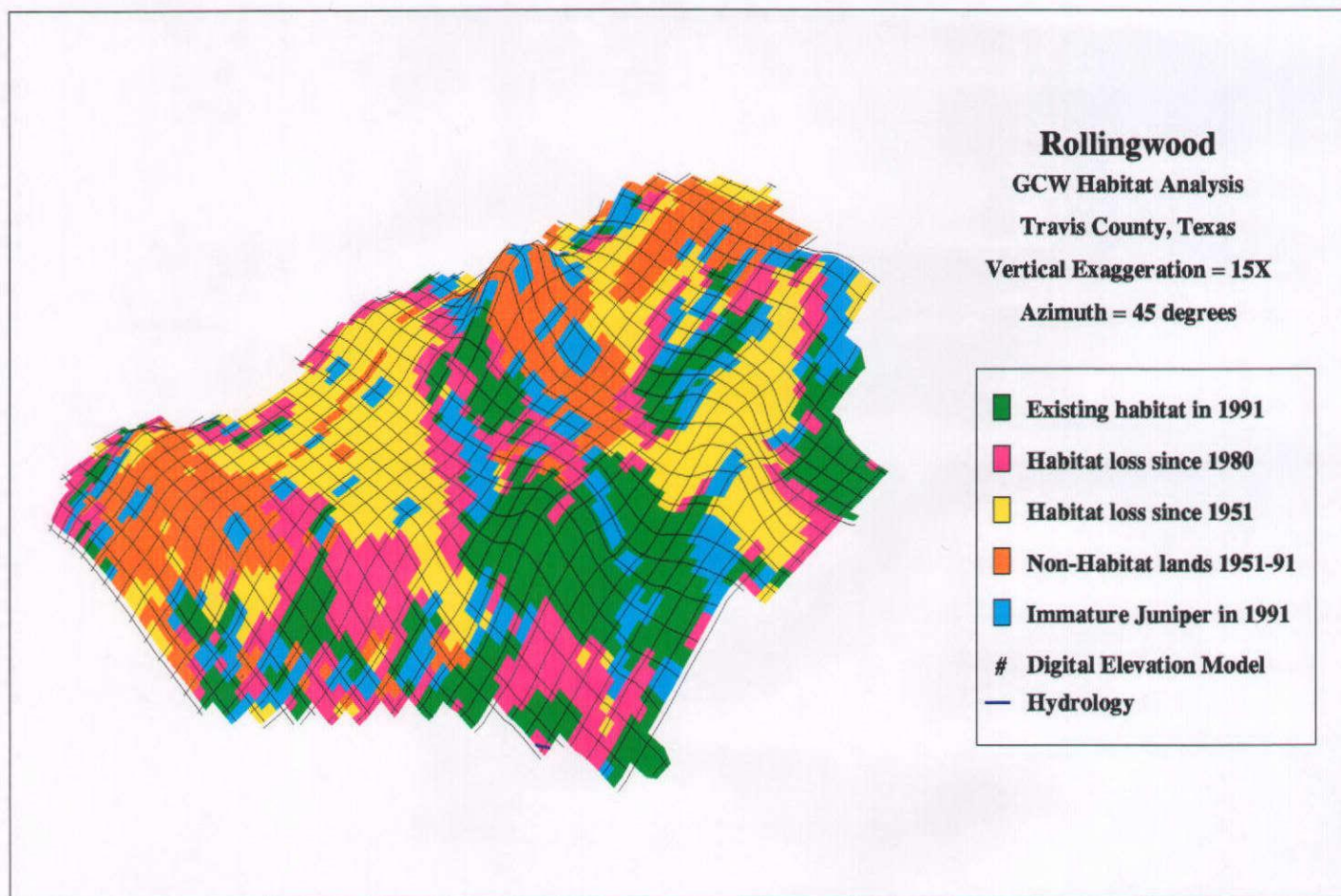


Map 11. Digital Elevation Model portraying topographic position of GCW habitat for the West Lake Hills study site.



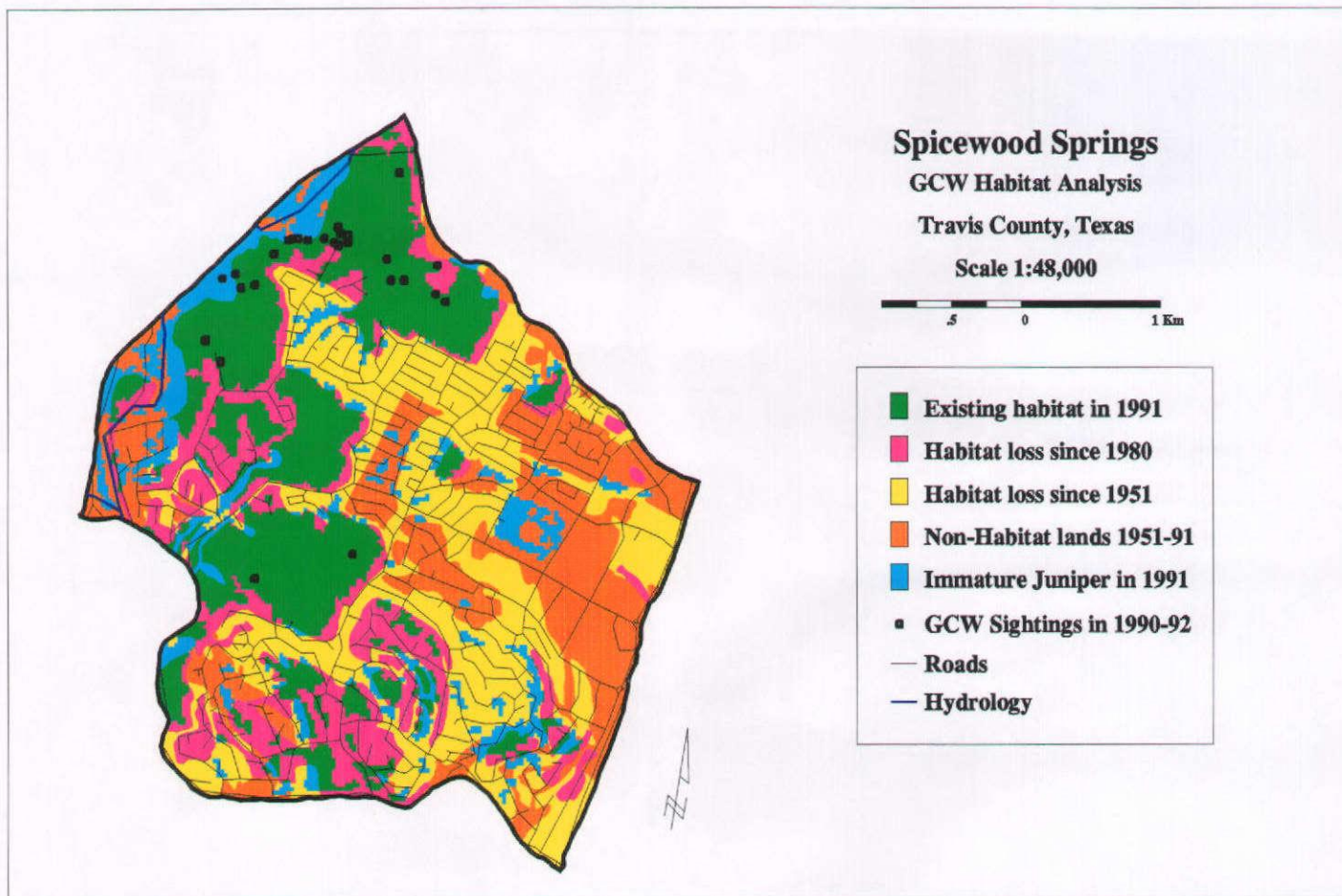


Map 12. Status of GCW habitat in Rollingwood study site for years 1951, 1980, and 1991 with 1990-1992 GCW sightings and 1988 road networks.

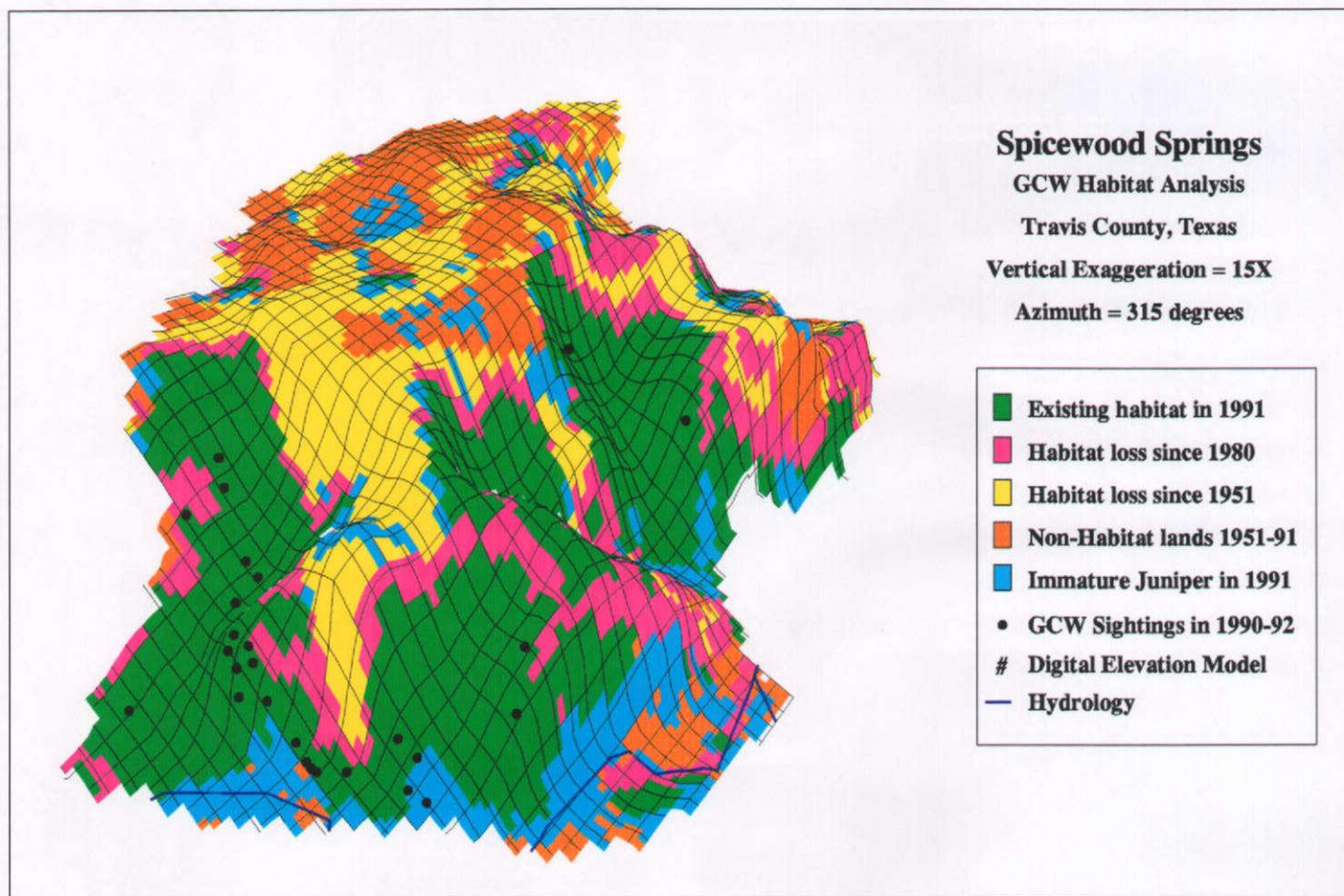


Map 13. Digital Elevation Model portraying topographic position of GCW habitat for the Rollingwood study site.



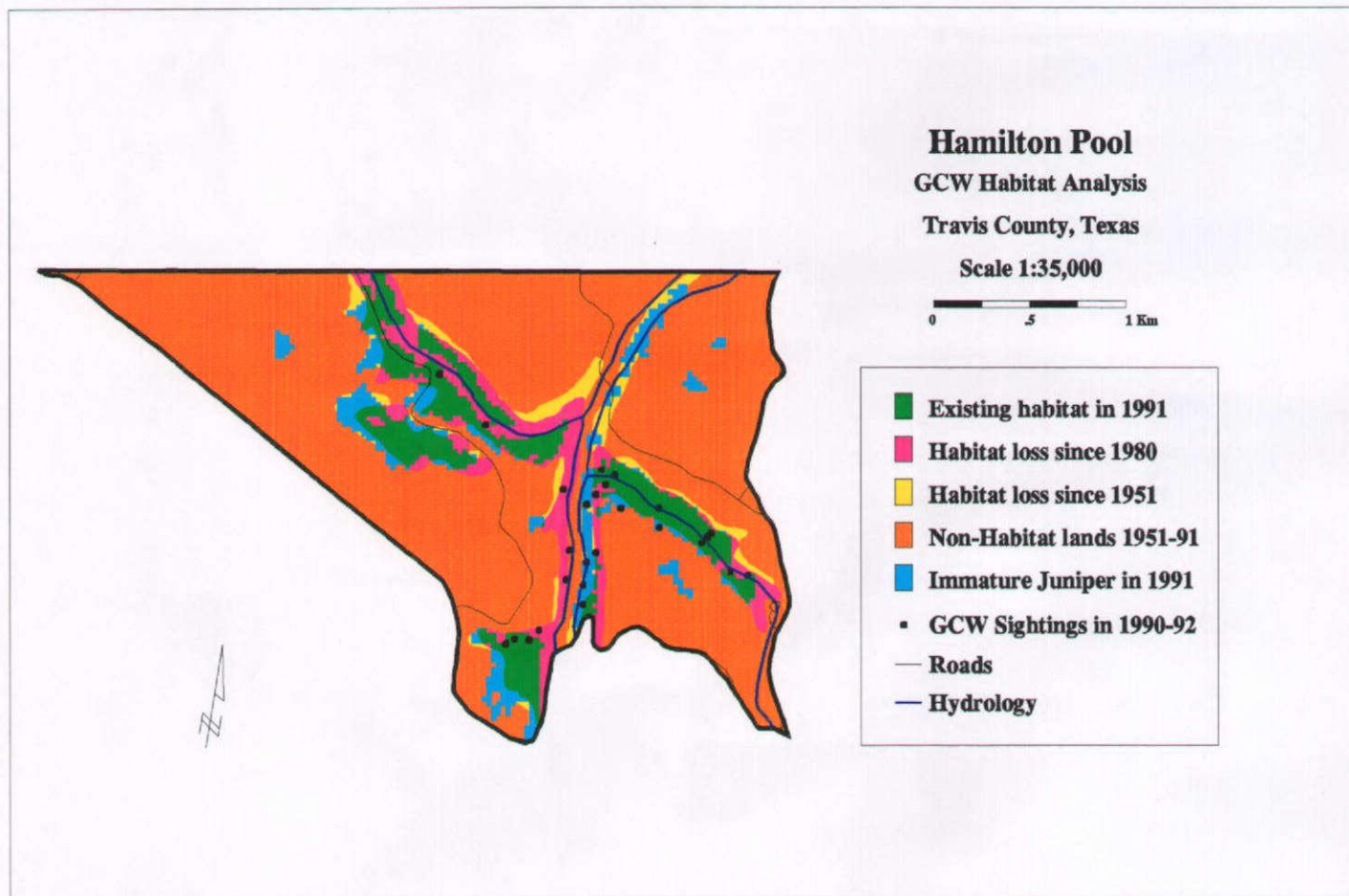


Map 14. Status of GCW habitat in Spicewood Springs study site for years 1951, 1980, and 1991 with 1990-1992 GCW sightings and 1988 road networks.

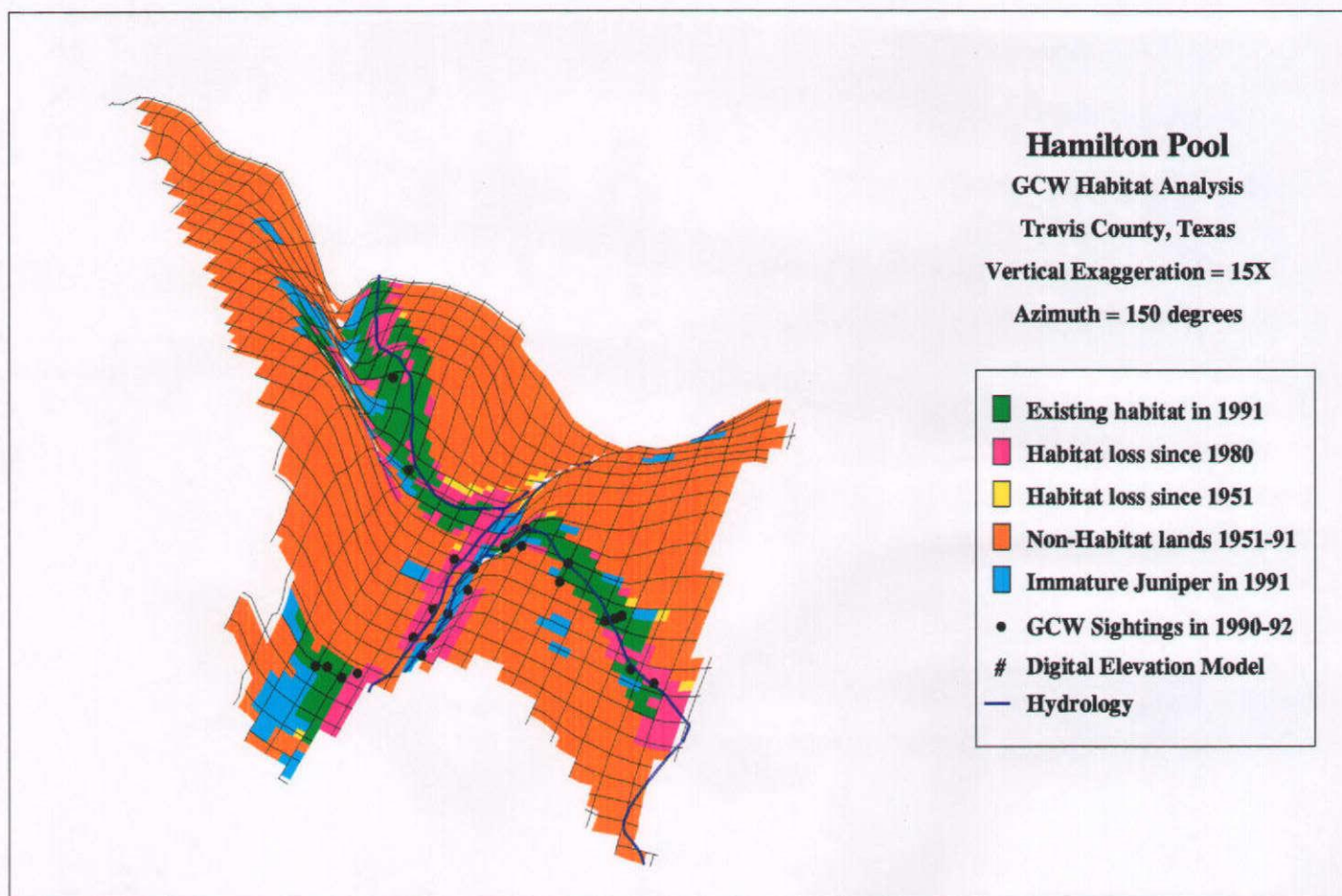


Map 15. Digital Elevation Model portraying topographic position of GCW habitat for the Spicewood Springs study site.





Map 16. Status of GCW habitat in Hamilton Pool study site for years 1951, 1980, and 1991 with 1990-1992 GCW sightings and 1988 road networks.



Map 17. Digital Elevation Model portraying topographic position of GCW habitat for the Hamilton Pool study site.



The 2 ½-D maps were created by 'draping' the planimetric habitat map over the digital elevation model of each site. Vertical exaggeration and a contrived viewer position provide the three-dimensional effect. The viewer position was chosen to give the most advantageous perspective on habitat within the study site. The result is a somewhat distorted view of habitat topographic position. Orientation of the 2 ½-D maps requires a certain amount of practice since the proper placement of North arrows is not feasible. Each 2 ½-D map has a compass azimuth noted in the legend. If a vertical line were drawn from the top map border, through the center of the map down to the bottom of the map, the resulting line would define a plane that passes through the noted compass azimuth.

Maps 2-17 incorporate a consistent color identification scheme. The habitat existing in 1991 is green, habitat lost since 1980 is purple while habitat lost since 1951 is yellow. Juniper woodlands less than ten years old (noted here as immature) are shown in light blue. Lands which were never identified as habitat during the 40 year period are orange. GCW sightings collected by the US Fish & Wildlife Service and Texas Park & Wildlife Department staff along with consulting biologists are shown as black dots. Sighting data is only available since listing of the GCW in 1990. Black lines show the roads existing in 1988.

### *Audubon*

The entire site experienced only a minor loss of GCW habitat in the years 1951-1980, with more losses experienced during 1980-1991 (Table 3). The large number of GCW sightings (10.8/100 ha, Table 4) correlated well with habitat delineation (Map 2). Most sightings were located in existing habitat, a few in immature juniper woodlands, and the overall preponderance of sightings are along stream canyons and hillsides (Map 3).

Table 3. Potential area (ha) of Golden-cheeked Warbler habitat for eight study sites in Travis County, Texas, for 1951, 1980 and 1991.

Study Site Name	Total Area (ha)	Habitat Area (ha)			Change (%)	
		1951	1980	1991	'51-80	'51-91
Audubon	3,420	1,571	1,356	1,160	-13.7	-26.2
Bull Creek	1,655	1,199	1,314	1,302	9.6	8.5
Emma Long Park	1,202	556	915	771	64.6	38.8
Reicher Ranch	1,069	591	486	421	-17.8	-28.8
West Lake Hills	1,833	1,281	960	859	-25.1	-33.0
Rollingwood	504	364	185	128	-49.2	-64.8
Spicewood Springs	1,393	956	567	462	-40.7	-51.6
Hamilton Pool	517	96	89	75	-7.4	-21.7

Table 4. Estimated habitat area, number of GCW sightings, and GCW sightings per 100 ha of habitat for eight study sites in Travis County, Texas.

Study Site Name	Number of GCW Sightings	Estimated Habitat Area (ha)	GCW Sightings per 100 ha of habitat <sup>a</sup> (#/100 ha)
Audubon	125	1,160	10.8
Bull Creek	261	1,302	20.1
Emma Long Park	45	771	5.8
Reicher Ranch	43	421	10.2
West Lake Hills	52	859	6.1
Rollingwood	0	128	0.0
Spicewood Springs	27	462	5.8
Hamilton Pool	26	75	34.6

<sup>a</sup> Calculation based on entire amount of estimated GCW habitat found at each site.

### *Bull Creek*

The site currently has many large contiguous blocks of habitat and a fairly constant level of habitat area (Table 3, Map 4). A heavy density of GCW sightings (20.1/100 ha, Table 4) occurred along the canyon hillside bordering Bull Creek with the remainder occurring on other hillside slopes (Map 5). Much of the site was classified as habitat, but the GCW sightings cluster in specific areas. The clustering may be biased by the non-systematic GCW sampling protocol. Although containing a low housing density overall, Bull Creek has high density in certain localized areas.

### *Emma Long Park*

Woodlands grew together to form more contiguous blocks during the period 1951-1980 (Table 3) which resulted in a significant gain in GCW habitat. A loss from 1980-1991 was minor in terms of acreage, but possibly significant in terms of spatial position because the loss occurred close to recent GCW sightings. The modest number of GCW sightings (5.8/100 ha, Table 4) within large contiguous blocks of habitat had an uneven, localized occurrence (Map 6). Sightings correlated well with habitat delineation, but uneven distribution of search effort left much of the classified habitat unvalidated. As in other areas, the majority of sightings occurred along sloping hillsides (Map 7). Minor road development within the site and only minimal urban encroachment overall provides for a stable level of habitat area.

### *Reicher Ranch*

Some GCW habitat was lost during 1951-1980 due mainly to the clearing of a sizable block in the southeastern region of the site, followed by a larger removal during 1980-1991 (Table 3, Map 8). A reasonable number of GCW sightings (10.2/100 ha, Table 4) closely follow the canyon contours (Map 9).

### *Westlake Hills*

Convolved canyons and winding streams dominate the area which results in a wide variation of habitat size and distribution. Locally intense loss of GCW habitat occurred during 1951-1980 in the northwest (Austin Country Club) and southern edge (Highway 2244). Moderate to heavy road development has occurred, especially along Westlake Drive which runs along the eastern and northern boundary of the site. Continued loss of habitat occurred during 1980-1991 (Table 3). A moderate number of very localized GCW sightings (6.1/100 ha, Table 4) correlated well with habitat delineation (Map 10). Most sightings occurred in existing habitat along stream canyons (Map 11).

### *Rollingwood*

A substantial removal of GCW habitat during 1951-1980 was the result of residential housing development, which continued to produce a rapid loss during 1980-1991. Only patchy, isolated habitat remnants persisted. On a percentage basis, Rollingwood had the greatest loss of GCW habitat of all sites (Table 3). The habitat loss has resulted in fragmentation of larger habitat patches into many small ones. There were no GCW sighting during 1990-92 (Table 4). Extensive road development and housing covers almost the entire site (Map 12) with remaining habitat found on a few mild slopes in the north central region (Map 13).

### *Spicewood Springs*

A substantial removal of GCW habitat during 1951-1980 was due to residential housing development, which continued to produce a rapid loss during 1980-1991. On a percentage basis, Spicewood Springs has had the second greatest loss of GCW habitat of all sites (Table 3). The site experienced extensive road development. The habitat loss resulted in fragmentation of the larger habitat patches into a few small ones. A small number (5.8/100 ha, Table 4) of very localized GCW

sightings in the remaining undeveloped canyons correlate well with habitat identification (Map 14). Sightings are most prevalent in existing habitat within canyons in the northwestern region (Map 15).

#### *Hamilton Pool*

The amount of GCW habitat underwent a minor change during 1951-1980, reflecting some minimal clearing (Table 3). The site had a large number of GCW sightings (34.6/100 ha, Table 4). GCW habitat indicated as loss during 1980-1991 may be an image classification or rectification problem since some GCW sightings occur in what was identified as habitat in 1980, but the sightings are offset from habitat delineated in 1991 (Map 16). These inconsistencies occur in small canyons (Map 17) that in 1980 possessed lower canopy cover than other habitat patches. The lower canopy cover may have prevented the image classification methods from identifying the patches. Other GCW sightings are scattered fairly regularly up and down stream courses which correlates with habitat identification.

### HABITAT/LAND USE ANALYSIS

#### *Habitat Patch Size Change*

Temporal change in potential GCW habitat over the forty year study period showed that some areas increased while others decreased (Table 3). Average habitat polygon sizes decreased over time for all study sites besides Emma Long Park (Table 5). Emma Long Park consisted almost entirely of protected city park land and showed the greatest overall increase in potential habitat extent (+38.8%). The substantial increase (64.6%) in habitat area that occurred in Emma Long Park during 1951-1980 resulted in the formation of a single large patch of habitat. This large habitat patch was only partially fragmented by road development during 1980-1991. The result was an increase of 32.0% in average habitat polygon size during the forty year study period. Bull Creek, another site which contained protected lands, exhibited

the only other increase in potential habitat area (8.5%) and had the smallest decrease in average habitat patch size (-13.2%). Audubon, Hamilton Pool, and Reicher Ranch suffered losses in habitat area (-26.2%, -21.7%, -28.8% respectively) and showed decreases in average habitat polygon size (-28.2%, -72.4%, -77.2% respectively) although each contained various amounts of preserved lands. Areas of intense development (Westlake Hills, Spicewood Springs, and Rollingwood) showed the largest decreases in potential habitat (-33.0%, -51.6% and -64.8% respectively) and average habitat polygon size (-78.1%, -96.7%, -92.7% respectively).

Table 5. Average polygon size (ha) of Golden-cheeked Warbler habitat for eight study sites in Travis County, Texas, for 1951, 1980 and 1991.

Study Site Name	Number of Polygons (n)			Average Polygon Size (ha)			Polygon Size Standard Deviation (S)			Change in Average Polygon Size (%)	
	1951	1980	1991	1951	1980	1991	1951	1980	1991	'51-80	'51-91
Audubon	71	41	73	22	33	16	79	64	118	50	-28
Bull Creek	8	5	10	150	263	130	361	434	354	75	-13
Emma Long Park	18	1	19	31	915 <sup>a</sup>	41	64	0 <sup>a</sup>	154	2863 <sup>a</sup>	32
Reicher Ranch	8	8	25	74	61	17	135	110	77	-18	-77
West Lake Hills	17	17	52	75	56	17	287	131	109	-25	-78
Rollingwood	11	22	53	33	8	2	79	10	6	-75	-93
Spicewood Springs	5	29	74	191	20	6	369	53	25	-90	-97
Hamilton Pool	6	3	17	16	30	4	14	17	6	85	-72

<sup>a</sup> In 1980, photo-interpretation identified one large habitat polygon in Emma Long Park.

#### *Habitat Topographic Position*

The majority of the habitat within all eight study sites for the three reference years falls between 4 and 8 degree slopes (Figure 2, Appendix 1). Care should be

taken when comparing this result to other analyses of GCW habitat slope data since the 1:250,000 DEM data contains slope values that have been averaged over approximately 90 meters of horizontal distance. Use of a higher resolution elevation data, such as a 1:24,000 DEM, would likely give a different result. Simultaneous Bonferroni confidence intervals were calculated for expected and actual occurrence of habitat slope types for each of the study sites (Figures 3 and 4, Appendix 2).

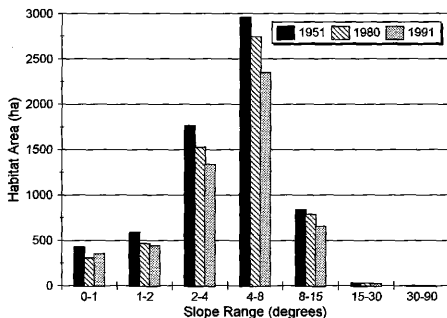


Figure 2. Combined total GCW habitat area separated by slope range for eight study sites in Travis County, Texas.

In each figure the expected proportion, shown as a filled circle, represents the proportional amount of ground surface available in each of the slope categories. Bonferroni simultaneous confidence intervals have been calculated for the proportion of habitat actually in each slope category as indicated by the brackets. Width of Bonferroni confidence intervals varies with sample size.

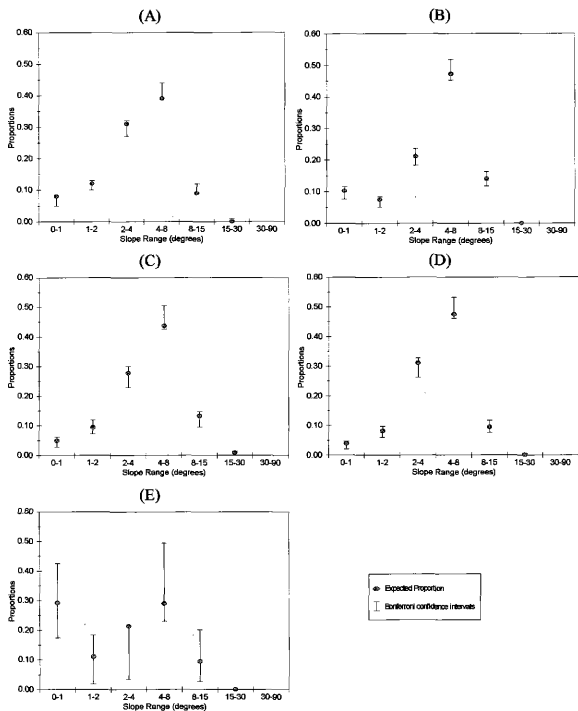


Figure 3. Bonferroni simultaneous confidence intervals for the occurrence of habitat in seven slope ranges for Audubon (A), Bull Creek (B), Emma Long Park (C), West Lake Hills (D), and Hamilton Pool (E) study sites.



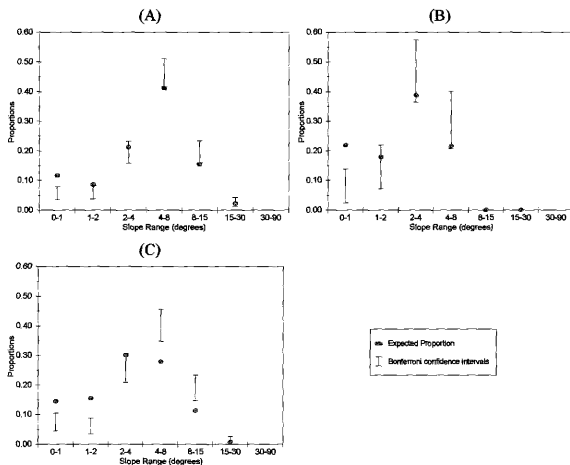


Figure 4. Bonferroni simultaneous confidence intervals for the occurrence of habitat in seven slope ranges for Reicher Ranch (A), Rollingwood (B), and Spicewood Springs (C) study sites.

For Audubon, Bull Creek, Emma Long Park, West Lake Hills, and Hamilton Pool study sites, each of the expected proportions (filled circles) occur within the confidence intervals. These data show that for these sites there is no statistically significant difference between actual occurrence of habitat and its availability for each of the slope code categories

Conversely, the confidence intervals calculated for the proportion of habitat in each slope category for Reicher Ranch, Rollingwood, and Spicewood Springs study sites, show a significant difference between actual occurrence and availability in at

least one of the six slope code categories ( $P < 0.05$ ). The habitat on flatter slopes occur in lower proportion than expected (i.e. habitat was removed) and habitat on steeper slopes occurs in a greater proportion (i.e. habitat was not removed).

#### *GCW Habitat Use*

Permit reports represent the best GCW survey data available, but some of these reports were limited to only presence/absence surveys and do not include more detailed GCW density and territorial mapping surveys. Therefore, sighting data contained in the FWS permit reports were not collected with equal time effort per unit area on all sites and observations were not systematically taken across all habitats within a site. For these reasons, a degree of caution is recommended when interpreting the relationships of GCW sightings to preferred habitat.

The total number of GCW sightings for each study site and GCW sightings per 100 ha (Figure 5) show that a larger number of GCW sightings occur in less developed, rural regions encompassing the Audubon ( $n=125$ , 10.8 sightings/100 ha), Bull Creek ( $n=261$ , 20.1 sightings/100 ha) and Reicher Ranch ( $n=43$ , 10.2 sightings/100 ha) sites. The most remote site in terms of urban proximity, Hamilton Pool, had the highest density of GCW sightings ( $n=26$ , 34.6 sightings/100 ha).

The statistical relationship between actual GCW sighting data and habitat slope was examined for each of the study sites using Bonferroni simultaneous confidence intervals (Figures 6 and 7, Appendix 3). For Audubon, Emma Long Park, Reicher Ranch, West Lake Hills, and Hamilton Pool study sites, the expected proportion of GCW sightings occur within the confidence intervals. These data show that there is no statistically significant difference between actual occurrence of GCW sightings and the availability of a given slope code category.

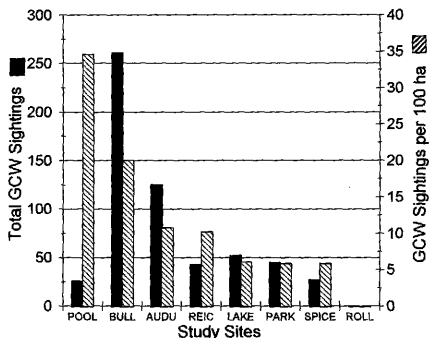


Figure 5. Total number of GCW sightings and GCW sightings per 100 ha for eight study sites in Travis County, Texas (BULL - Bull Creek, PARK - Emma Long Park, AUDU - Audubon, REIC - Riecher Ranch, LAKE - West Lake Hills, SPICE - Spicewood Springs, POOL - Hamilton Pool, ROLL - Rollingwood).

Only Bull Creek and Spicewood Springs are statistically significant ( $P < 0.05$ ). The GCWs were seen in greater than expected proportions on steeper slopes ( $4-8^\circ$ ) in Bull Creek and less than expected proportions on flat slopes ( $0-1^\circ$ ). GCWs were seen in less than expected proportion on mild slopes ( $2-4^\circ$ ) in Spicewood Springs

#### *Continuity Index (CI)*

When combined with known habitat losses (Table 3), the smaller average habitat patch sizes (Table 4) indicated an increasing level of habitat fragmentation. The level of fragmentation that occurred during the forty-year time period was examined by comparing the CI for the reference years of 1951, 1980 and 1991.

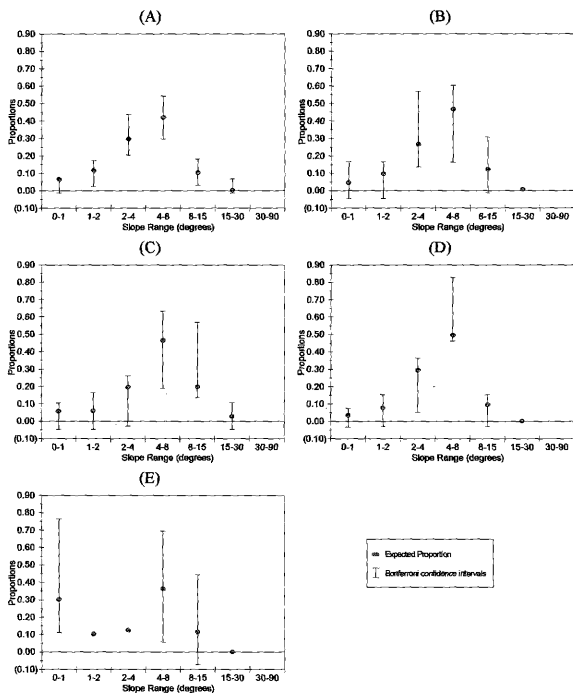


Figure 6. Bonferroni simultaneous confidence intervals for the occurrence of GCW sightings in seven slope ranges for Audubon (A), Emma Long Park (B), Reicher Ranch (C), West Lake Hills (D), and Hamilton Pool (E) study sites.

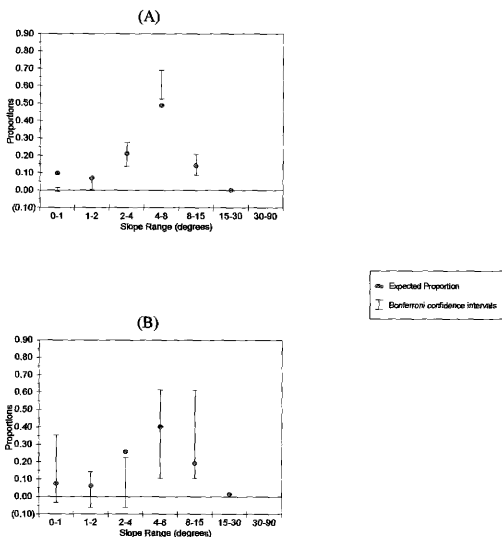


Figure 7. Bonferroni simultaneous confidence intervals for the occurrence of GCW sightings in seven slope ranges within Bull Creek (A) and Spicewood Springs (B) study sites.

Increasing trends (Figure 8, Appendix 4) in CI values were found in Audubon (+0.77), Bull Creek (+0.39), Emma Long Park (+0.61), Reicher Ranch (+0.15) and Hamilton Pool (+0.07). Decreasing trends in CI occurred in West Lake Hills (-0.11), Rollingwood (-0.80) and Spicewood Springs (-0.64).

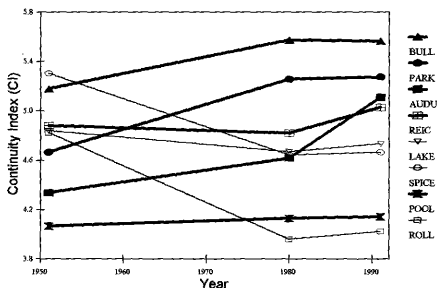


Figure 8. Continuity index (CI) for eight study sites in Travis County, Texas (BULL - Bull Creek, PARK - Emma Long Park, AUDU - Audubon, REIC - Reicher Ranch, LAKE - West Lake Hills, SPICE - Spicewood Springs, POOL - Hamilton Pool, ROLL - Rollingwood).

### *Road Density*

For the each study site, the amount of habitat area lost since 1951 and the linear length of road was determined and a road density was calculated (Figure 9, Appendix 5). The highest road density in former habitat was found in Spicewood Springs (0.104 km/ha), followed by Rollingwood (0.082 km/ha), West Lake Hills (0.059 km/ha), Emma Long Park (0.054 km/ha), Bull Creek (0.044 km/ha), Audubon (0.021 km/ha), Hamilton Pool (0.014 km/ha), and Reicher Ranch (0.003 km/ha). A comparison of the amount of habitat lost during 1951-1990 and the corresponding road density indicate an increasing trend in road density from protected sites to heavily urbanized sites.

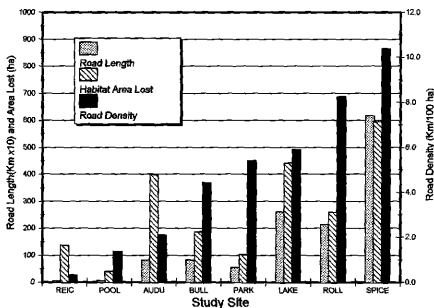


Figure 9. Habitat area lost (1951-1991), road length and road density in former habitat for eight study sites in Travis County, Texas (BULL - Bull Creek, PARK - Emma Long Park, AUDU - Audubon, REIC - Riecher Ranch, LAKE - West Lake Hills, SPICE - Spicewood Springs, POOL - Hamilton Pool, ROLL - Rollingwood).

#### *Road Density and Continuity Index*

A comparison of road density in former habitat and corresponding continuity index (Figure 10) shows that study sites with lower road densities (Reicher Ranch, Hamilton Pool, Audubon, Bull Creek, and Emma Long Park) had a higher average continuity index (avg. CI=5.02) than those study sites with greater road densities (West Lake Hills, Rollingwood, and Spicewood Springs; avg. CI=4.48). The lower CI values indicate fragmentation occurring in study sites impacted by urbanization.

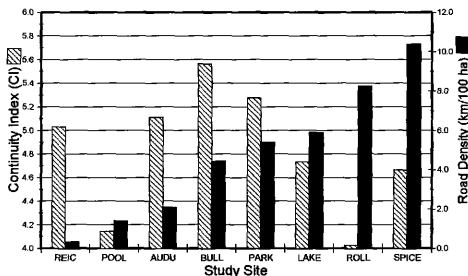


Figure 10. Comparison of continuity index (CI) and road density in former habitat for eight study sites in Travis County, Texas (BULL - Bull Creek, PARK - Emma Long Park, AUDU - Audubon, REIC - Riecher Ranch, LAKE - West Lake Hills, SPICE - Spicewood Springs, POOL - Hamilton Pool, ROLL - Rollingwood).

#### *Road Density and GCW Sightings*

As road density increases in areas adjacent to existing GCW habitat, a reduction in GCW sightings would be one indicator of decreased habitat use. A comparison of road density in former habitat with the number of GCW sightings for eight sites shows a general trend ( $r = -0.58$ ) of decreased GCW sightings as road density increases (Figure 11).



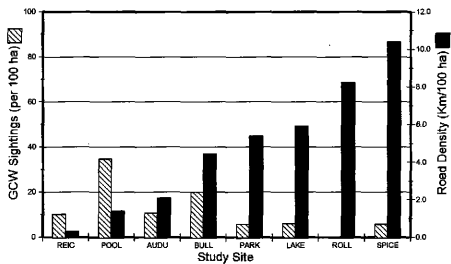


Figure 11. GCW sightings and road density in former habitat for eight study sites in Travis County, Texas (BULL - Bull Creek, PARK - Emma Long Park, AUDU - Audubon, REIC - Riecher Ranch, LAKE - West Lake Hills, SPICE - Spicewood Springs, POOL - Hamilton Pool, ROLL - Rollingwood).

## DISCUSSION

The primary objective of this study was to analyze the effects of land use practices on fragmentation pattern, habitat distribution and, to the extent possible, relate these variables to GCW habitat condition. Urban development was found to be the primary driving variable in land use change during the forty year study period (Figure 12). A fragmented landscape pattern was observed in each of the sites impacted by urbanization. Urbanization reduced total habitat acreage and changed the habitat patch size distribution by breaking larger habitat patches into numerous small ones. The analysis showed that residential expansion had an adverse effect on GCW habitat extent, connectivity and condition. Only in more remote study areas was there little change in the habitat distribution. Land use relationships to habitat fragmentation, road density, topographic variables, continuity index and bird sightings are generalized in Figure 13.

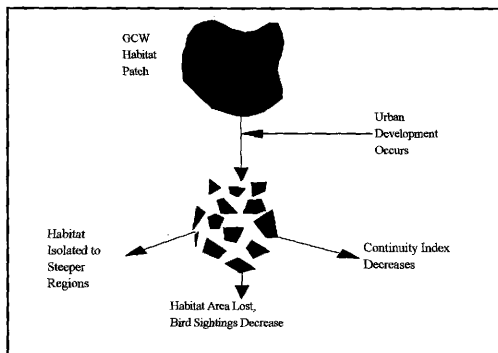


Figure 12. Impact of urban development on intact GCW habitat.

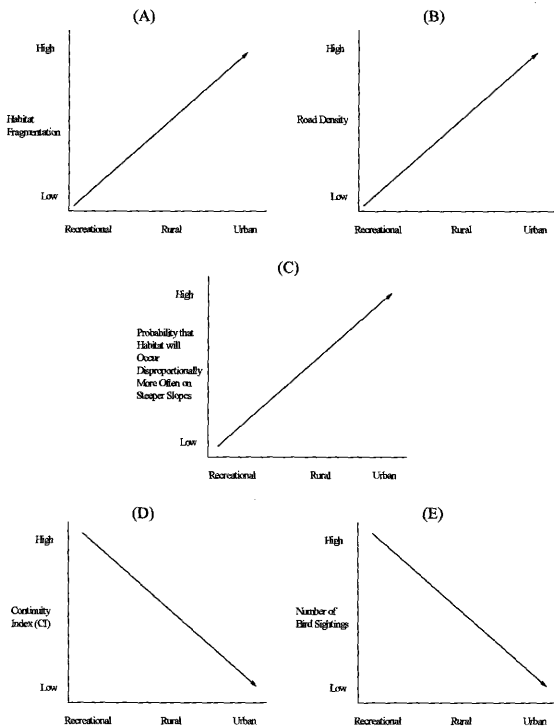


Figure 13. Generalized relationships of land use to habitat fragmentation (A), road density (B), topographic variables (C), continuity index (D) and GCW sightings (E).

In reference to the five study hypotheses:

1. Aerial photographs, satellite imagery and a GIS were shown to provide a reasonable method for monitoring GCW habitat in Travis County, Texas.
2. In study sites fragmented by urbanization, GCW habitat was more concentrated on steeper slopes. In sites unaffected by urbanization, GCW habitat occurred in all available topographic types.
3. GCW sightings did occur in expected proportions on all available topographic types in six of the eight study sites. GCW sightings were biased in favor of habitat on steeper slopes in one rural study site while sightings were under-represented on mild slopes within one urban study site.
4. CI was a reliable indicator of fragmentation and trends in CI were able to discriminate between different patterns resulting from recreational, rural and urban land use.
5. Using GCW sighting data as a measure of habitat condition, higher road densities in former habitat was correlated with decreasing GCW habitat condition.

Substantial portions of GCW habitat were found on mild slopes. Several study sites exhibited this characteristic, even though GCW habitat is more often noted as occurring in more rugged regions with a greater degree of slope. One complicating factor contributing to this result is the low resolution DEM (90m<sup>2</sup>, 1:250,000 scale) which effectively ‘flattened’ or ‘averaged’ the slopes over long horizontal distances. A higher resolution DEM (30m<sup>2</sup>, 1:24,000) would have been advantageous, but it was not available from USGS at the time of the study. Shaw (1989) used a 1:250,000 DEM to analyze the slope of 7,429 ha of GCW habitat in Llano County, TX. She found fifty-seven percent of GCW habitat occurred on slopes of less than 2°, twenty percent of the habitat on 2°-4° slopes and twenty-three percent of the habitat on slopes steeper than 4°. In Travis County, I analyzed 5,178 ha of GCW habitat and found only fifteen percent of the GCW habitat on slopes less than 2°, with twenty-six percent of the habitat on 2°-4° slopes and forty-five percent of the habitat on 4°-8° slopes, as well as fourteen percent on slopes greater than 8°. Differences in the two studies are likely due to the more rugged topography found in Travis County, TX. More importantly, both studies point to a significant amount of GCW habitat

occurrence in mildly sloped terrain. Analysis of the topographic (slope) data in this report is valid within the bounds of this particular study since it is all derived from the same base data. The habitat slope values are numerically relative to one another. Caution should be taken when quantitatively comparing this GCW habitat slope data to other studies that use spatial data of higher resolution.

If it is assumed that ecological processes create the most viable habitat in the canyon areas, then conservation of non-rugged areas adjacent to the canyons would not be a critical issue. But at several study sites in Travis County, Texas, land-use decisions have driven the spatial positioning of the habitat. As hypothesized, I found a habitat bias for steeper slopes in sites impacted by major amounts of urban disturbance. Land use decisions have excluded habitat to the rugged regions. Land managers should be concerned about the habitat loss in the mildly-sloped areas adjacent to the canyons. Fragmentation and anthropogenic land use practices have degraded adjacent habitat condition. The converse was true in sites unaffected by urbanization. Sites with minimal urban disturbance did not indicate a habitat bias towards steeper slopes nor a degradation in habitat condition.

In theory, animals select the best habitat in a landscape only when the number of animals competing for the available habitat is low. If we assume steeper habitats to be better, then habitat selection may be occurring in Bull Creek, but in six of seven other sites, habitat use as indicated by GCW sighting data conforms to habitat availability implying that the entire range of habitat types are important. Results indicate an overall agreement with my hypothesis that GCW sightings would not be biased in favor of steeper slopes. As noted previously, a degree of caution should be used when interpreting the GCW sighting data. Often the GCW survey data contained in the USFWS permit reports were limited to only presence/absence surveys and do not include more detailed GCW density and territorial mapping surveys. Sighting data were not collected with equal time effort per unit area on all sites and observations were not systematically taken across all habitats within a site.

Also, I would caution that accepting a direct correlation between habitat slope and GCW sightings may be a reckless assumption in and of itself. Other factors such as the clearing of adjacent habitat, intrusion of feral animals, competition with urban-adapted species, noise, light, or other human disturbance may effect GCW habitat quality. These factors are related to the intensity of human land use and need further investigation to determine their effects on the long term condition of GCW habitat.

The ultimate goal of the spatial analysis was to relate CI to land use (meaning a protected landscape of natural vegetation would be discriminated from an urbanized site by its continuity index). Reed et al. (1996) applied several patch indices (number of patches, mean patch area, mean patch perimeter, total perimeter and mean patch shape) to identify patch related landscape changes. Their mean patch shape parameter, based on a corrected perimeter/area index by Baker and Cai (1992), is similar to the CI used in this analysis. By analyzing data from aerial photographs taken 43 years apart, Reed et al. (1995) were able to detect the introduction of roads into a forested area of south eastern Wyoming. In this study of the Hill Country of Texas, study sites with higher CI values in 1991 (Bull Creek, Emma Long Park, Audubon, and Reicher Ranch) were the same sites that had the lowest percentage losses in habitat area and the largest average habitat patch sizes. Study sites with lower CI values in 1991 (West Lake Hills, Rollingwood, and Spicewood Springs) were also the sites with the highest percentage losses in habitat area and the smallest average patch sizes. Hamilton Pool site is a good example of how thin, angular habitat patch shape (in this case the habitat patches occur within a riparian corridor) can result in a low CI value even though the study site is not in an urban setting.

Vogelmann (1995), developed the CI method and analyzed spatial patterns in New England. He found a statistically significant correlation between increasing population levels and decreasing CI values in the township regions he studied. In my results, CI was inversely related to fragmentation. As CI values decreased in the West Lake Hills, Spicewood Springs and Rollingwood study sites, total habitat area and

average habitat patch size decreased too. These results indicate that fragmentation increased while CI decreased.

Increasing CI values implied a reduction in fragmentation for the Emma Long Park and Bull Creek study sites during the 1951-1980 period. Increased total habitat area and larger average patch sizes verify a reduced level of fragmentation in these two sites during 1951-1980.

Confounding indications occur in the Audubon study site during the forty year study period. The amount of habitat area and average habitat patch size in the Audubon site decreased (implying fragmentation) while CI values increased (a decrease in CI would normally be expected). This scenario can be explained with the established geometrical relationships of the CI. The surviving habitat patches would have to be shaped more like circles (high area to perimeter ratio, more interior habitat) than thin rectangles (low area to perimeter ratio, minimal interior habitat), a situation which rarely occurs during the process of urban development. In the Audubon study site, GCW habitat losses were not caused by road building or any other indicator of urban growth. Juniper-oak woodland removal occurred for some other reason, quite likely to create more a esthetic parkland appearance. Therefore, continuity index proved to be a flexible and effective metric for tracking changes in patch geometry resulting from urban-induced fragmentation.

Usable habitat occurred in both fragmented patchworks as well as in large contiguous blocks. The Audubon habitat was broken up into many patches, but there were many GCW sightings. Compared to the Bull Creek site which had a large contiguous patch and clusters of GCW sightings in certain areas. In both areas, most GCW sightings occurred on the sloping canyon walls with fewer sightings in regions of lesser topographic relief. The key feature which both areas shared was a low density of adjacent human land use. Apparently, land use played a more significant role than slope in determining the condition of GCW habitat in these study areas. In a different example, Bull Creek and Spicewood Springs were across a valley from each

other. They had similar topography, soils, and hydrology. They were both part of the Bull Creek Watershed which fed the Colorado River. They differed only in their respective levels of urbanization. Spicewood Springs had characteristically diverse topography. The uplands were cleared, with the remaining habitat restricted to the slopes. A series of interviews conducted with several respected and experienced Austin birdwatchers ( R. Adams, M. Adams, R. Rowlett, and F. Webster pers. com.) revealed field records going back into the 1950's. The records showed that Spicewood Springs was a prolific GCW site. In fact until the mid 1970's, it was one of the most reliable places to go observe GCW. Now, there are only a few GCW sightings on some of the remaining slopes. As hypothesized, former habitat areas adjacent to the remaining habitat has characteristically high road densities. Bull Creek contained similar undulating topography, but retained large contiguous habitat blocks. The mild slopes next to the canyon regions had not been developed for residential housing. GCWs were found in relatively high numbers. Interview data suggested a similar scenario of habitat loss in the Rollingwood site, birdwatchers described several GCW viewing areas which are no longer viable.

Roads have been recognized as a severe threat to wildlife and road density in former habitat can be used to probe the processes of habitat loss and subsequent land use intensity (Noss and Cooperider 1994). Roads stimulate development and resulting habitat destruction. A decision to build a new road or upgrade a existing road should be considered carefully when GCW habitat is involved. In many cases, a critical assessment will show the need to not only prevent new roads, but close and re-vegetate existing road corridors. In my analysis, higher road densities in former habitat were related to both fragmentation indices (CI) and lower GCW sighting frequencies. The fragmentation occurs in two stages: (1) loss of GCW habitat in a landscape through road building and urban development followed by (2) partitioning of remaining habitat into isolated, small pieces. Studies of landscape change in other parts of the world (Weins 1989) foretell that the inevitable consequence of urban



development in Travis County, Texas will be a disjunct pattern of small GCW habitat patches scattered in a matrix of human-altered land. The urbanized matrix surrounding the habitat patches will be a rich source of predators and other intruders. Just as important as the loss of habitat area, the extensive amount of edge created by urban networks of roads, utilities and right-of-ways will create dangers for GCW. Competitors and parasites, such as blue jays and cowbirds, utilize the edge of disturbed habitat patches and are capable of invading the interior as well. Nests parasitism by brown-headed cowbirds is most intense near habitat edges and declines toward the patch interior (Brittingham and Temple 1983). The physical environment near edges produces a different microclimate and corresponding distinct vegetation structure (Ranney et al. 1981). Different animal species are associated with edge habitat (Johnston and Odum 1956) and for a patch-interior species like the GCW, a small patch may be entirely edge. Most edge-dwelling species are widespread and at minimal risk of extinction in human-dominated landscapes (Diamond 1976, Terborgh 1976). Interior-dwelling neotropical migrants like the GCW are a greater concern (Whitcomb et al. 1981), especially in regions such as Travis County, Texas where so much habitat is now edge habitat. Rendered useless by predation and parasitism, the fragmented patchwork of habitat islands will be uninhabitable by GCW. Clearly, future conservation strategy for the GCW should maximize the amount of unfragmented habitat in the landscape.

## CONCLUSION

This study utilized remote sensing and a geographic information system (GIS) to determine past changes and current risks associated with various land use practices within the range of the Golden-cheeked Warbler in Travis County, Texas. The analysis addressed temporal variation in the spatial heterogeneity of GCW habitat and land use planning considerations. Statistical data on land use change and spatial analysis parameters were investigated. Relationships of land use to habitat condition and structure were analyzed. Principal findings were that GCW habitat patches occurred throughout the landscape in a protected environment while urbanization concentrated habitat in steeper regions. Bird sightings indicated that GCWs used habitat in a wide array of topographic classes. Calculation of a Continuity Index (CI) gave a usable measure of habitat fragmentation by quantifying land use changes. Finally, road density in former habitat was negatively correlated with GCW use of remaining habitat.

Several notable limitations were encountered during the study. The unavailability of a 1:24,000 USGS DEM for Travis County, Texas, reduced the resolution and overall utility of the topographic analyses. A lack of GCW biological information detailing fecundity, survivorship, dispersal rates, home range size, minimum viable population size, habitat occupation densities, habitat functional relationships, census levels and sighting frequencies all served to limit the depth and rigor of the analysis. Funding and time limitations prevented more extensive field work to collect independent GCW census data and perform more field verification of the habitat classification, both of which would have provided more robust accuracy assessments.

Researchers should heed a strong warning and think carefully before attempting to combine aerial photo-interpretation and satellite imagery classification data in ways similar to those presented in this study. Major problems arose when attempting to compare the different data sources because of scale differences and

conflicting classification methodologies. Inherent differences in classification methodology contributed to concerns about habitat area estimation and habitat patch shape comparisons. Adjustments and normalizations required to manipulate the different data sources to a common metric became an additional origin of error. It is recommended that time series or spatial comparison analyses similar to this study should adhere to a single data source and avoid combining aerial photo-interpretation with satellite imagery classification.

Future research should focus on obtaining more complete biological information on GCW, especially relating to GCW habitat core area requirements and GCW responses to human-caused disturbance. Relating directly to this study, substantial benefits would be derived from comparing the 1991 satellite imagery classification with an aerial photo-interpretation of 1991 GCW habitat in Travis County, Texas. Also, analyses combining photo-interpretation and satellite image classification would benefit from the development of better normalization techniques to facilitate synthesis of these two remote sensing methodologies.

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## APPENDIX 1

Combined habitat area (ha) listed by slope range from eight study sites in Travis County, Texas, for 1951, 1980 and 1991.

Slope (degrees)	Habitat Area (ha)		
	1951	1980	1991
0-1	429.45	308.85	355.04
1-2	588.37	466.35	440.16
2-4	1,766.59	1,527.43	1,341.94
4-8	2,959.61	2,747.74	2,349.00
8-15	840.41	788.18	657.65
15-30	29.81	31.83	27.23
30-90	0.00	0.00	0.00

## APPENDIX 2

Simultaneous confidence intervals using the Bonferroni approach for occurrence of habitat slope types within eight study sites in Travis County, Texas.

Study Site Name	Habitat Slope Codes	Expected Proportion of Occurrence ( $P_E$ )	Actual Proportion of Occurrence ( $P_i$ )	Bonferroni Confidence Intervals for $P_i$		
Audubon	1	0.08	0.06	0.05	$\leq P_i \leq$	0.08
	2	0.12	0.11	0.10	$\leq P_i \leq$	0.13
	3	0.31	0.30	0.27	$\leq P_i \leq$	0.32
	4	0.39	0.42	0.39	$\leq P_i \leq$	0.44
	5	0.09	0.10	0.09	$\leq P_i \leq$	0.12
	6	0.00	0.00	0.00	$\leq P_i \leq$	0.01
Bull Creek	1	0.10	0.10	0.08	$\leq P_i \leq$	0.12
	2	0.07	0.07	0.05	$\leq P_i \leq$	0.08
	3	0.21	0.21	0.18	$\leq P_i \leq$	0.24
	4	0.47	0.49	0.45	$\leq P_i \leq$	0.52
	5	0.14	0.14	0.12	$\leq P_i \leq$	0.16
	6	0.00	0.00	0.00	$\leq P_i \leq$	0.00
Emma Long Park	1	0.05	0.04	0.03	$\leq P_i \leq$	0.06
	2	0.09	0.10	0.07	$\leq P_i \leq$	0.12
	3	0.28	0.26	0.23	$\leq P_i \leq$	0.30
	4	0.44	0.47	0.43	$\leq P_i \leq$	0.51
	5	0.13	0.12	0.10	$\leq P_i \leq$	0.15
	6	0.01	0.01	0.00	$\leq P_i \leq$	0.01
Reicher Ranch	1	0.12	0.06	0.04	$\leq P_i \leq$	0.08 *
	2	0.09	0.06	0.04	$\leq P_i \leq$	0.08 *
	3	0.21	0.19	0.16	$\leq P_i \leq$	0.23
	4	0.41	0.46	0.42	$\leq P_i \leq$	0.51 *
	5	0.15	0.20	0.16	$\leq P_i \leq$	0.23 *
	6	0.02	0.03	0.01	$\leq P_i \leq$	0.04
West Lake Hills	1	0.04	0.03	0.02	$\leq P_i \leq$	0.05
	2	0.08	0.08	0.06	$\leq P_i \leq$	0.10
	3	0.31	0.29	0.26	$\leq P_i \leq$	0.33
	4	0.47	0.50	0.46	$\leq P_i \leq$	0.53
	5	0.09	0.10	0.08	$\leq P_i \leq$	0.12
	6	0.00	0.00	-0.00	$\leq P_i \leq$	0.00
Rollingwood	1	0.22	0.08	0.02	$\leq P_i \leq$	0.14 *
	2	0.18	0.15	0.07	$\leq P_i \leq$	0.22
	3	0.39	0.47	0.36	$\leq P_i \leq$	0.57
	4	0.22	0.31	0.21	$\leq P_i \leq$	0.40
	5	0.00	0.00	0.00	$\leq P_i \leq$	0.00
	6	0.00	0.00	0.00	$\leq P_i \leq$	0.00
Spicewood Springs	1	0.14	0.08	0.05	$\leq P_i \leq$	0.10 *
	2	0.16	0.06	0.03	$\leq P_i \leq$	0.09 *
	3	0.30	0.26	0.21	$\leq P_i \leq$	0.31
	4	0.28	0.40	0.35	$\leq P_i \leq$	0.46 *
	5	0.11	0.19	0.15	$\leq P_i \leq$	0.23 *
	6	0.01	0.01	0.00	$\leq P_i \leq$	0.03
Hamilton Pool	1	0.29	0.30	0.17	$\leq P_i \leq$	0.42
	2	0.11	0.10	0.02	$\leq P_i \leq$	0.18
	3	0.21	0.12	0.03	$\leq P_i \leq$	0.21
	4	0.29	0.36	0.23	$\leq P_i \leq$	0.49
	5	0.10	0.11	0.03	$\leq P_i \leq$	0.20
	6	0.00	0.00	0.00	$\leq P_i \leq$	0.00

\* Indicates a difference at the 0.05 level of significance.

## APPENDIX 3

Bonferroni simultaneous confidence intervals for occurrence of GCW sightings on slope types within seven<sup>a</sup> study sites in Travis County, Texas.

Study Site Name	GCW Sighting Slope Codes	Expected Proportion of Occurrence ( $P_{0i}$ )	Actual Proportion of Occurrence ( $P_i$ )	Bonferroni Confidence Intervals for $P_i$		
Audubon	1	0.06	0.03	-0.01	$P_1$	0.07
	2	0.11	0.10	0.02	$P_2$	0.17
	3	0.30	0.32	0.20	$P_3$	0.44
	4	0.42	0.42	0.30	$P_4$	0.54
	5	0.10	0.11	0.03	$P_5$	0.18
	6	0.00	0.03	-0.01	$P_6$	0.07
Bull Creek	1	0.10	0.00	-0.01	$P_1$	0.01 *
	2	0.07	0.04	0.01	$P_2$	0.07
	3	0.21	0.20	0.14	$P_3$	0.27
	4	0.49	0.61	0.52	$P_4$	0.69 *
	5	0.14	0.15	0.09	$P_5$	0.21
	6	0.00	0.00	0.00	$P_6$	0.00
Emma Long Park	1	0.04	0.06	-0.05	$P_1$	0.17
	2	0.10	0.06	-0.05	$P_2$	0.17
	3	0.26	0.35	0.14	$P_3$	0.57
	4	0.47	0.38	0.16	$P_4$	0.60
	5	0.12	0.15	-0.01	$P_5$	0.31
	6	0.01	0.00	0.00	$P_6$	0.00
Reicher Ranch	1	0.06	0.03	-0.05	$P_1$	0.11
	2	0.06	0.06	-0.05	$P_2$	0.17
	3	0.19	0.12	-0.03	$P_3$	0.26
	4	0.46	0.41	0.19	$P_4$	0.63
	5	0.20	0.35	0.14	$P_5$	0.57
	6	0.03	0.03	-0.05	$P_6$	0.11
West Lake Hills	1	0.03	0.02	-0.03	$P_1$	0.08
	2	0.08	0.06	-0.03	$P_2$	0.15
	3	0.29	0.21	0.05	$P_3$	0.36
	4	0.50	0.65	0.46	$P_4$	0.83
	5	0.10	0.06	-0.03	$P_5$	0.15
	6	0.00	0.00	0.00	$P_6$	0.00
Spicewood Springs	1	0.08	0.16	-0.03	$P_1$	0.35
	2	0.06	0.04	-0.06	$P_2$	0.14
	3	0.26	0.08	-0.06	$P_3$	0.22 *
	4	0.40	0.36	0.11	$P_4$	0.61
	5	0.19	0.36	0.11	$P_5$	0.61
	6	0.01	0.00	0.00	$P_6$	0.00
Hamilton Pool	1	0.30	0.44	0.11	$P_1$	0.76
	2	0.10	0.00	0.00	$P_2$	0.00
	3	0.12	0.00	0.00	$P_3$	0.00
	4	0.36	0.38	0.06	$P_4$	0.69
	5	0.11	0.19	-0.07	$P_5$	0.45
	6	0.00	0.00	0.00	$P_6$	0.00

<sup>a</sup> Rollingwood site did not contain any GCW sightings.

\* Indicates a difference at the 0.05 level of significance.

## APPENDIX 4

Continuity Index (CI) of potential Golden-cheeked Warbler habitat for eight study sites in Travis County, Texas, for 1951, 1980 and 1991.

Study Site Name	Continuity Index (CI) <sup>a</sup>			Change	
	1951	1980	1991	'51-80	'51-91
Audubon	4.34	4.62	5.11	+0.28	+0.77
Bull Creek	5.18	5.57	5.56	+0.39	+0.39
Emma Long Park	4.67	5.26	5.27	+0.59	+0.61
Reicher Ranch	4.88	4.82	5.03	-0.06	+0.15
West Lake Hills	4.84	4.67	4.73	-0.17	-0.11
Rollingwood	4.82	3.96	4.03	-0.86	-0.80
Spicewood Springs	5.30	4.64	4.67	-0.66	-0.64
Hamilton Pool	4.07	4.13	4.14	+0.06	+0.07

<sup>a</sup> CI values range are rarely greater than 6.00 or below 4.00.

## APPENDIX 5

Potential Golden-cheeked Warbler habitat area lost (ha) between 1951-1991, and road density in the former habitat for eight study sites in Travis County, Texas.

Study Site	Habitat Area Lost	Length of Roads in	Road Density in
Name	1951-1991 (ha)	Former Habitat (km)	Former Habitat (km/ha)
Audubon	398.54	8.36	0.021
Bull Creek	187.34	8.32	0.044
Emma Long Park	102.96	5.56	0.054
Reicher Ranch	137.80	0.45	0.003
West Lake Hills	441.89	26.10	0.059
Rollingwood	259.67	21.42	0.082
Spicewood Springs	595.17	61.79	0.104
Hamilton Pool	39.67	0.55	0.014

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